Measuring Conventional and Alternative Exhaust Emissions from a Gas Turbine Engine

By

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Submitted to the graduate degree program in Civil, Environmental, and Architectural Engineering and the Graduate Faculty of the University of Kansas in partial fulfillment of the requirements for the degree of Master of Science.

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Date Defended: December 11th, 2012

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Measuring Conventional and Alternative Exhaust Emissions from a Gas Turbine Engine

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Date approved: December 15th, 2012

Abstract

Rising fuel costs and energy demands, combined with growing concern over greenhouse gas emissions, have led to increased interest in the use of renewable fuels to help meet increasing worldwide demand and reduce atmospheric CO_2 emissions from transportation sources. The global demand for aviation is estimated to have a growth rate of 5% for the next 15 years. This growth will be contributed by both developed and developing economies and if the emission remains unchecked, this is estimated to contribute to 15-20% of global emissions by 2050. This research investigates a method of establishing small batch-scale testing at the University of Kansas for gas turbine exhaust emissions. A Semtech-DS portable gaseous emissions analyzer developed by Sensors-Inc. was used for exhaust sampling of a PT6 turboprop engine on a test-stand located in an outdoor test cell. Exhaust emissions were collected for CO_2, CO, NO_x, and HC for three fuels (Jet A, HRJ, and FT) and analyzed for comparison in units of grams of pollutant per kilogram of fuel burned. This study successfully accomplished the establishment of small-batch scale emissions collection from a gas turbine engine at the University of Kansas. Limited results were obtained for the alternative fuel blends and more data needs to be collected before environmental impacts can be accurately assessed. Chemical composition data on the fuel feedstocks and blends would be useful in future testing to aid in deciphering the emission results.

Acknowledgements

I would like to take this opportunity to thank the University of Kansas – Environmental Engineering Department, for giving me the chance to study and work with some of the finest individuals in their respective fields. Special thanks to my committee members Dr. Belinda Sturm, Dr. Ray Taghavi, and Dr. Edward Peltier for this wonderful learning opportunity. This research was finically supported by the Transportation Research Institute (TRI) as part of the NASA EPSCoR project, without their support this project could not have happened.

Special thanks go out to Andy Pritchard for his assistance with anything needed while working at the Mal Harned Aerospace Hanger. Appreciation to Dr. Dennis Lane for allowing me to use his emissions sampling equipment and Jing Guo and Yue Zhong for guiding me with the operation of the Semtech-DS analyzer. Also, thanks to the Sensor's technicians that helped diagnose the issues encountered during sampling. I must thank Alex Karwas and Evan Beckman who operated the gas turbine engine that samples were collected from and KSU Salina for allowing the use of their engine and equipment. Other thanks to Alan Walker for drilling out the probe housing design and everyone else that helped or provided assistance on this project. Finally, I would like to thank my family and loved ones for their continued support through this entire process.

Table of Contents

Nomenclature

Abbreviation	Definition
°C	degrees Celsius
AMB	Automotive Micro-Bench
AMT	Advanced Micro Trubines
APU	auxiliary power unit
ASTM	American Society for Testing and Materials
BtL	biomass-to-liquid
CED	compact engine display
CF	carbon filter
CFR	Code of Federal Regulations
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
cSt	centiStokes
CtL	coal-to-liquid
ECU	electric control unit

EGT	Exhaust Gas Temperature
EI	Emission Index
EPA	Environmental Protection Agency
ES	electric start
FADEC	Full Authority Digital Engine Control
FID	Flame Ionization Detector
FT	Fischer-Tropsch
GC	gas chromatograph
GCC	Global Climate Change
GHG	Greenhouse Gas
GtL	gas-to-liquid
H:C	hydrogen to carbon ratio
H_2O	water vapor
HC	hydrocarbon
Hg	Mercury
HNO_3	Nitric Acid
HRJ	hydroprocessed renewable jet

Hz	Hertz
ICAO	International Civil Aviation Organization
IPCC	Intergovernmental Panel on Climate Change
IPK	iso-paraffinic kerosene
IR	infrared
kg	kilogram
KS	Kansas
KSU	Kansas-State University
LCA	life cycle analysis
LED	light-emitting diode
LTO	landing take-off cycle
m^3	cubic meter
mass %	percentage by mass
mg	milligram
MJ	megajoule
mL	milliliter
mm^2	millimeters squared

N_2	diatomic nitrogen
NAAQS	National Ambient Air Quality Standards
NCF	no carbon filter
NDIR	non-dispersive infrared
NDUV	non-dispersive ultraviolet
NO	Nitric Oxide
NO_2	Nitrogen Dioxide
NO_3^-	Nitrate Ion
NO_x	Oxides of Nitrogen
O_2	diatomic oxygen
O_3	Ozone
PM	Particulate Matter
ppm	parts per million
s	second
SO_2	sulfur dioxide
SO_x	Sulfur Oxides
syngas	synthesis gas

THC	total hydrocarbons
TIT	Turbine Inner Temperature
UHC	unburned hydrocarbon
U.S.	United States
UV	ultraviolet
VOC	volatile organic compound
vol %	percentage by volume
w/w %	percentage on a weight by weight basis

List of Figures

List of Tables

Measuring Conventional and Alternative Exhaust Emissions from a Gas Turbine Engine

1. Introduction

Since 1970 the United States has had to import oil from other counties to meet its ever rising demands [1]. This situation often puts the U.S. in a weak position when negotiating political and diplomatic agreements and forces them to do business with instable or totalitarian regimes. Transportation in the United States is almost completely dependent on petroleum, accounting for nearly 60% of the nation's use of petroleum, with 56% being imported [2]. The share of the petroleum used by air transportation is 12%, which correlates to about 20 billion gallons per year for aviation. Petroleum has always been the aviation fuel of choice because of its ease of handling, cost, operational reliability, high energy content, and fast combustion. Fuel currently represents the largest operating cost for U.S. airlines. Nearly 100% of the fuel used in aviation operation today is derived from petroleum, and the cost, supply, and emissions associated with this fuel potentially limit the security and sustainability of aviation [3]. Worldwide petroleum reserves are expected to be depleted in less than 50 years at the present rate of consumption [4]. "Although considerable uncertainty and latitude exist in identifying a timeline for the depletion of petroleum reserves and the onset of severe global warming, the following projections and facts largely hold [2]. That is, the global energy demand will double by 2050, especially recognizing the heightened needs by several rapidly developing countries; more petroleum is being used than is being discovered, such that the global petroleum reserve is on the path of net depletion; and our dependence on oil from geo-politically unstable regions could strongly affect our economic and political well-being. Furthermore, uncertain as it may be, the

Intergovernmental Panel on Climate Change (IPCC) estimates that in the absence of additional corrective action to reduce anthropogenic greenhouse gas (GHG) emissions, the global temperature will rise between 1 and 6.4 °C by 2100." In view of these indicators, especially the possibility that the trend could accelerate as developing countries achieve further economic prosperity, it is vital to actively develop options for alternative fuels, including alternative aviation fuels, so that a successful transition to the post-petroleum era can be achieved.

The primary drivers in the development and use of alternative fuels for air transportation would be the security and cost of supply [2]. The purchase of fuel currently represents the largest operating cost for U.S. airlines, in which every 1-cent per gallon increase in fuel price translates into an additional $190 million in annual costs for the commercial aviation industry. One major driver for a change to biofuels, and indeed for making biofuel production viable, is the volatility in price, and generally increasing cost, of crude oil [5]. However there is another pressing reason to promote the use of carbon neutral fuels to replace fossil fuels, that of global warming or global climate change (GCC). Finding sufficient supplies of clean energy for the future is one of society's most nerve-racking challenges and is intimately linked with global stability, economic prosperity, and quality of life. Soaring energy demand in developing nations is beginning to create intense competition for the world's dwindling energy resources.

Mitigating climate change from the aviation sector can be simplified to consuming less energy through improvements in aircraft technology or operational efficiency and reducing the climate impacts of the energy source through the use of alternative fuels [6]. Demand for alternatives to petroleum fuel is increasing the production of biofuels from food crops such as corn, sugarcane, and palms [7]. As a result, land in undisturbed ecosystems is being converted to biofuel feedstock production while existing agricultural land is also being diverted to biofuel

production. Soils and plant biomass are the two largest biologically active storage sites of terrestrial carbon, together containing about 2.7 times more carbon than the atmosphere [7]. Converting native habitats to cropland releases CO_2 as a result of burning or microbial decomposition of organic carbon stored in plant biomasses and soils. At least for current biofuel technologies, any strategy to reduce greenhouse gas emissions that cause land conversion from native ecosystems to cropland is likely to be counter-productive. If biofuels are to help mitigate global climate change, studies suggest that they need to be produced with little reduction of the storehouse of organics in the soils and vegetation of natural and managed ecosystems.

For biofuels to be considered sustainable, the feedstock should be produced domestically without competing with food production, should not use fresh water supplies, and should have neutral greenhouse gas emissions after a life cycle analysis (LCA) [7,8]. Biofuels derived from algal biomass feedstocks are generating considerable interest around the world. The use of algae can be a suitable alternative because it is the most efficient biological producer of oil on the planet and a versatile biomass source [9]. With this in mind algal derived lipids could serve as a major contributor to our goal of energy independence. Algal biofuel production has several aspects that have combined to capture the interest of researchers and scientists. These include: high per-acre productivity, feedstocks based on non-food resources, use of otherwise non-productive and non-arable land, utilization of a wide variety of water resources, mitigation of greenhouse gas release into the atmosphere, and production of both biofuels and valuable co-products [10]. Algae can be cultivated on otherwise non-productive land that is unsuitable for agriculture. It can also be grown in brackish, saline, and wastewater that has little competing demand, offering the prospect of a biofuel that does not further tax already limited resources.

Unlike terrestrial crops whose failure costs an entire growing cycle, an algal pond can be re-inoculated to resume production in a matter of days.

Biofuels derived from vegetable oils may be considered sustainable if sufficient quantities of plants can be cultivated. Furthermore, this can be viewed as a step toward a "carbon neutral" fuel economy. U.S. scientists advise that "biofuels should receive policy support as substitutes for fossil energy only when they make a positive impact on four important objectives: energy security, greenhouse gas emissions, biodiversity, and the sustainability of the food supply" [8]. An effective system would have to guarantee that biofuels use a resource, such as a waste product or carbon-poor lands, which will not trigger large emissions from land use change. Potential biofuel benefits originate in the annual carbon uptake from growing a feedstock, but growing that feedstock will typically require up-front release of carbon previously sequestered on that land over decades. Therefore, it is crucial that a biofuel feedstock must not initially release more carbon than it will accumulate over the growing season.

1.1 Jet Engines and Unique Characteristics

The gas turbine engine powers the aviation industry. It is made-up of three main components: a compressor, the combustion chamber, and turbines [11]. A fan sucks air into the compressor where temperature and pressure are increased. This compressed air is then sprayed with fuel and ignited by a spark in the combustion chamber, which increases volume and energy. The burning gas blasts out of the combustion chamber and into the turbines where the aerodynamic energy is turned into mechanical energy. The exhaust gases then exit through a nozzle at the back of the engine, generating thrust to force the engine, and plane, forward. There are three different jet engine classifications based on precisely what the turbines of the engine do.

The most basic case is the turbojet engine. In all cases the turbines power the engine's compressor, but in the turbojet case that is all it does. Turboprop engines use the energy of the turbines to also power propellers that aid in generating thrust. Similar to a turboprop engine, turbofan engines take advantage of the turbine energy to power a fan at the front of the engine.

The transportation sector has three main engine types: spark ignition, compression ignition, and gas turbine. The gas turbine engine and reciprocating engine cycles can be seen in Figure 1. Spark ignition and compressions ignition are both employed for use in the automotive sector while gas turbines provide more power, which is needed in the aviation industry [12]. Also, the altitude that which gas turbines are forced to function at enforces fuel flow restrictions to ensure that fuel will be delivered to the engine under low temperature conditions [13]. Alternative fuels, such as biodiesel, were not produced for use in gas turbine engines, such that they do not meet specifications for aviation fuel. Gas turbines are fueled by kerosene, not diesel or gasoline such as compression and spark ignition engines. Kerosene, diesel, and gasoline fuels all emit a variety of exhaust species that can be detrimental to air quality and the global climate [14]. These exhaust species come from differing combustion parameters and chemical composition of the fuels.

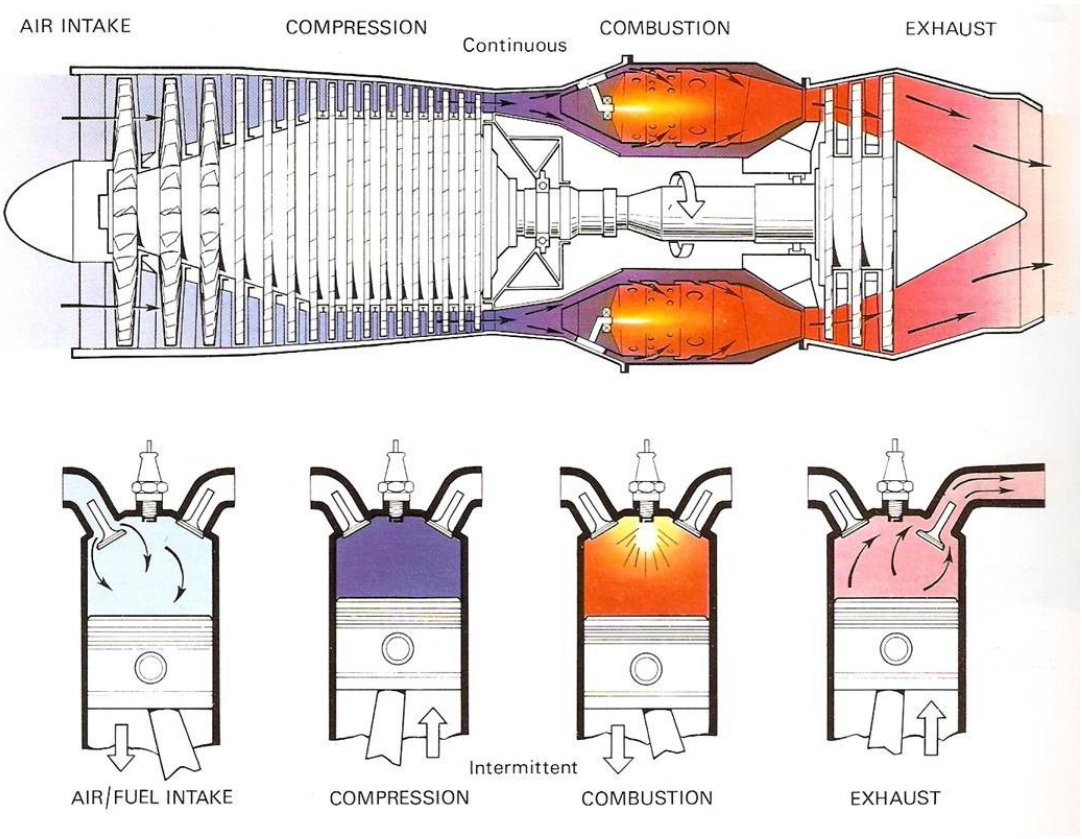

Figure 1. Gas turbine and Reciprocating Engine cycle [15]

Specifications for transportation fuels are established by American Society for Testing and Materials (ASTM) [17]. Diesel fuel contains a large fraction of kerosene, actually about 75% kerosene; thus, these fuels are relatively similar but have some important differences. A barrel of crude oil contains 42 gallons, of which only 10-15% becomes kerosene stock [16]. Kerosene fits in between the heavier cut of diesel and the lighter cut of gasoline in the distillation process when refining crude oil [18]. Diesel has a heavier selection of carbon chains ranging from C_{12} – C_{18} while kerosene is slightly lighter with a range from C_8 – C_{16}. Kerosene is a higher quality fuel than road transport fuels and therefore must meet some more stringent specifications, such as flash point, density, and cold flow properties [13]. Standards for commercial Jet A or Jet A-1 aviation fuel can be seen below in Table 1, Jet A is used in commercial U.S. flights, while Jet A-1 is used commercially in the rest of the world. Table 2 provides certain chemical composition

information about selected fuels: diesel, Jet A, bio-diesel, and vegetable oils (a possible biofuels feedstock).

Table 1. Basic requirements for Jet A and Jet A-1 fuel (ASTM D1655)

COMPOSITION		
Acidity, total mg KOH/g	Max	0.10
Aromatics: One of the following requirements shall be met:		
1. Aromatics, vol %	Max	25
2. Aromatics, vol %	Max	26.5
Sulfur, mercaptan, mass %	Max	0.003
Sulfur, total mass %	Max	0.30
VOLATILTY		
Distillation		
Distillation temperature, °C		
10% recovered, temperature (T10)	Max	205
Final boiling point, temperature	Max	300
Distillation residue, %	Max	1.5
Disillation loss, %	Max	1.5
Flash point, °C	Min	38
Density at 15°C, kg/m^3		775 to 840
FLUIDITY		
Freezing point, °C	Max	(-) 40 Jet A (-) 47 Jet A-1
Viscosity at (-) 20°C, mm^2/s	Max	8.0
COMBUSTION		
Net heat of combustion, MJ/kg	Min	42.8
One of the following requirements shall be met:		
1. Smoke point, mm, or	Min	25
2. Smoke point, mm, and	Min	18
Naphthalenes, vol, %	Max	3.0
THERMAL STABILITY		
2.5 h at control temperature of 260°C, min		
Filter pressure drop, mm Hg	Max	25
CONTAMINANTS		
Existent gum, mg/100 mL	Max	7

Table 2. Chemical composition comparison [4]

Properties	Diesel	Jet-A	Straight Vegetable Oils	Bio-Diesel
Density (kg/m^3)	827.4	807	900-940	860-900
Kinetic Viscosity (cSt at 40 °C)	1.7283	0.88	30-40	3.5-5
Flash Point (°C)	44	39	230-280	120-180
Cloud Point (°C)	-6		-4 to 12	-3 to -12
Pour Point (°C)	-16	-47	-12 to 10	-15 to 5
Lower Calorific Value (MJ/kg)	43	43.23	38-39	39-41
Ignition Temperature	250	220	325-370	177
Cetane no.	45-55	55	37-42	48-60
Stoichiometric air/fuel ratio	14.6	14	13.8	13.8
Carbon (%, w/w)	80.33	80-83	76.11	77-81
H_2 (%, w/w)	14	10-14		12
N_2 (%, w/w)	1.76		0	0.03
O_2 (%, w/w)	1.19		11	9-11
Sulfur (%, w/w)	<0.4	<0.4	0	<0.03

Aviation fuels are composed of a variety of components of different chemical composition. Refiners use components to balance the key specifications that produce the optimum fuel for specific applications and operating environments [19]. Several key fuel specifications contribute to optimum performance, some benefitting engine performance and others the environment. To create a fuel for optimum performance, refiners focus on the fuel's cetane number, density, heating value, low temperature properties, and thermal stability. Concurrently, they also control the sulfur, aromatic, and distillation range of the fuel to create an environmentally friendlier fuel that meets mandated regulations.

Refiners measure the fuel's cetane number to determine ignition time; for optimum performance and power, auto ignition must occur with the minimum possible delay [19]. Fuels with larger cetane numbers ignite more readily, providing shorter ignition delay times. Cetane

numbers above 50 provide optimum operation and low particulate matter emissions. Aromatics are added in various amounts to the fuel to volumetrically increase yields. Aromatics increase the density of the fuel, and thus the heating value, and improve cold flow properties. Yet, aromatics decrease the cetane number of the fuel and have been identified as contributors to emissions of nitrogen oxides; higher concentrations of aromatic compounds increase flame temperature during combustion, which contributes to NO_x formation [19].

The heating value, or heat of combustion, of the fuel is a measure of the amount of available energy content from a known quantity of fuel. The heating value is directly proportional to the fuel density [19]. Fuels with higher heating values result in a higher power output and increased fuel economy. Two factors can be altered to change the heating value of a fuel; they are (1) increasing the aromatic content and (2) changing the distillation profile by raising the initial boiling point and/or the end boiling point. However, these factors are limited by other fuel properties. Changing the aromatic content is restricted by the minimum cetane number specification and adjustments to the distillation profile are limited by the 90% distillation maximum temperature specification. The amount of paraffin, iso-paraffin, and aromatic content of the fuel affects the low temperature properties of the fuel, in turn affecting the operating performance of the fuel. Studies show that fuels containing a higher percentage of iso-paraffin compounds result in a fuel with much better low temperature properties.

The volatility characteristics of the fuel are expressed in terms of the temperature at which successive portions of the fuel are distilled from a sample of the fuel under controlled heating in a standardized apparatus [19]. The distillation, or boiling range, of a fuel depends on the fuel's chemical composition and therefore influences other properties such as viscosity, flash point, cetane number, and density. Extension of the boiling range towards lower temperature

leads to a fuel that has better low temperature properties such as pour and cloud point, but the cetane number is lowered reducing combustion efficiency. When the boiling range is moved toward higher temperatures refiners can include heavy compounds in their final blend, thereby increasing their yield of fuel. However, the heavier compounds could produce increased soot emissions and cause choking of the injection nozzle. The back-end volatility of the fuel, expressed as the 90% or 95% distillation recovery temperature, has some effect on emissions. When the volatility is reduced, a slight increase in hydrocarbon and carbon monoxide emissions and a small decrease in nitrogen dioxide emissions are observed [19].

Increasing the fuels' density increases the power output of the engine per unit volume of fuel consumed while reducing the fuel density reduces the nitrogen oxides and organic matter emissions [19]. Research shows that reductions in density as small as 5% can reduce particulate matter emissions by as much as 20% in older engines, with more modern engines showing further reductions. Lower nitrogen oxides emissions stem from the lower peak pressures and temperatures associated with burning low density fuels. Thus, current engine design focuses on how to weigh the positive emission reductions associated with lower density fuels against performance factors, primarily more power, associated with higher density fuels.

There are many factors that must be considered when evaluating the applicability of a fuel for use in the aviation sector. Among the most important factors are the thermo-physical properties of the fluid, including the volatility, density, heat capacity, transport properties, and thermal stability [20]. Of these properties, the volatility is critical because it is very sensitive to compositional variability and is crucial for engine operation. The three categories of properties that are needed for the aviation biofuels are related to: (1)The conditions of storage of energy onboard an aircraft along with the properties related to high altitude conditions of use – the

minimum value for fuel energy content is 42.8 MJ/kg and its density is restricted to 775-840 kg/cm^2 [13]. At high altitude, the temperature is low and hence, the freezing point of the fuel should be below -47°C and the viscosity should be low (below 8 mm^2/s at -20°C) to allow pumping of the fuel. (2) The injection and combustion of the fuel imposes constraints on fuel viscosity, volatility, and composition. Although the tendency to form particles restricts the aromatic content in aviation fuels, they play an important role from a lubricity point of view. Too low of a concentration may cause problems, as aromatics are used for seals swell to prevent leakage. (3) Safety as well as hardware longevity imposes specifications on volatility, flash point, and compatibility with materials so there is no corrosion.

Alternative jet fuels must have characteristics sufficiently similar to current petrojet fuel regardless of the feedstock and refining processes, i.e. be "drop-in" fuels [21]. A drop-in fuel is fully compatible as well as interchangeable with conventional jet fuel [13]. This does not require adaptation of the aircraft or of the infrastructure, does not imply any restrictions on the domain of the aircraft usage, and does not require any new certification of the system. Aviation infrastructure and equipment have a usual lifetime of 30 - 40 years; thus, the drop-in requirement has been recognized as a major requirement for the development and approval of the first alternative fuels in aviation [18]. A non-drop-in fuel would require complete different infrastructure along with adaptation of engines with the need of new deployment of a fuel distribution system worldwide.

First generation biofuels have raised important issues regarding land use change, impact on food process, and irrigation water. Moreover, some of the first generation fuels like ethanol and biodiesel are not suitable for aviation in terms of meeting high performance or safety specifications required for jet fuel [13]. Methanol and ethanol are also inferior to Jet-A because

an extra oxygen atom in their molecular structure not only does not play the role of a fuel but actually adds weight to it. Indeed, this concern is present for practically all biofuels, including biodiesel, which have oxygen atoms in their molecular structures. In regards to making a surrogate jet fuel composition, the synthetic fuel would be ideally comprised of: (1) a carbon length of C_8-C_{16}, (2) paraffins making-up 70-85% of the composition and including normal paraffins, iso-paraffins, and cyclic paraffins, (3) an aromatics content less than 25% but including toluene, n-propylbenzene, and naphthalenes, and (4) containing less than 1% trace compounds including dibenzothiophene, diethylene glycol monomethyl ether, and phenol [2].

Any oxygenated fuel to be considered as a replacement or alternative to a conventional hydrocarbon transportation fuel must be critically examined from many different viewpoints. Biodiesel molecules consist of more oxygen atoms than the alcohols, typically two or three, which reduce the heat content of the fuel [22]. This reduction is not substantial, because the basic hydrocarbon functional group is large; although it is still a matter of concern for aviation use [2]. A second concern is the high freezing point of the bio-oil, typically around 0°C as compared with about -40°C for jet fuels. Both of these concerns require further processing of bio-oil to achieve characteristics suitable as a drop-in aviation fuel.

There are currently two biojet production technologies available: 1) hydrotreating/hydrocracking processes which use vegetable oils as the feedstock, and 2) gasification followed by Fischer-Tropsch (FT) synthesis and syn-crude upgrading [21]. The FT route requires the production of a synthesis gas (syngas) from a suitable feedstock, which is then fed into a liquid conversion process. Syngas, namely a mixture of hydrogen and carbon monoxide, may be derived from coal (CtL), gas (GtL), or biomass (BtL). The initial products are mainly straight-chain hydrocarbons, which are further cracked into smaller ones and then

rearranged to yield the desired composition in terms of the volatility range and chemical properties [2]. Depending on the product requirements, the catalyst is selected for production of long chain paraffins. This synthetic crude is then upgraded (hydroprocessed, hydrocracked, and separated) to produce commercial product. Depending on the operating temperature, pressure, and syngas composition of the FT process, it is possible to control the output carbon number. A lack of aromatics in FT fuels reduces the fuel density and could also inhibit swelling of the seals in the engine fueling system and hence can cause fuel leakage. In fact, most biofuels produced by current refinery processes do not contain aromatic compounds, which account for up to 25% of petrojet by volume and are needed for proper lubrication and sealing of the engine [21]. This, along with the requirement to meet fuel density specifications for aviation fuel, requires that the biojet be blended with petrojet. Currently, a 50/50 blend by volume is the accepted norm.

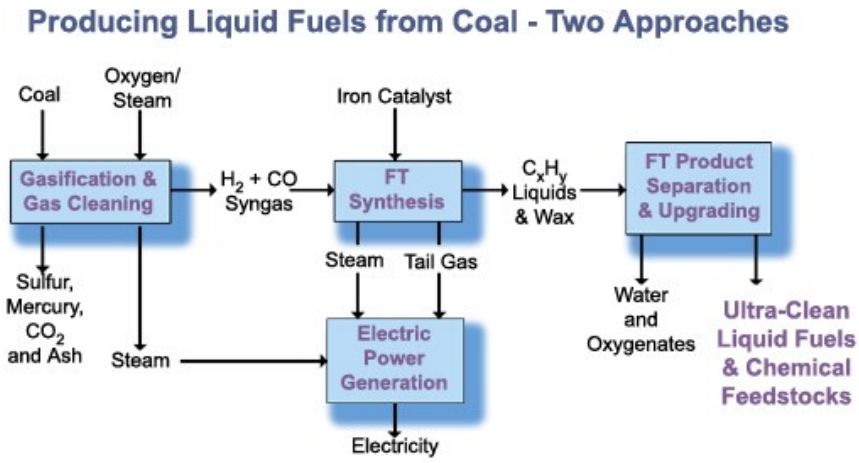

Figure 2. Fischer-Tropsch Production Pathway [23]

Hydro-processed oils producing 'Green Jet' fuel from plant oils or animal fats are often referred to as hydro-processed renewable jet (HRJ) fuel. The hydro-processing reaction is carried out by combined hydrodeoxygenation and hydrogenation [20]. This results in a stream of C_{14} to C_{18} normal paraffins that are then hydroisomerized and hydrocracked. In this process, the bio-

derived oils, triglycerides and free fatty acids are first converted to shorter chain diesel range paraffins by reactions with hydrogen (which removes the oxygen atom and increases heat content) and by converting the olefins to paraffins (which increases the thermal stability of the fuel) [2]. Hydroprocessing employs hydrotreatment to first deoxygenate and remove undesirable materials, including nitrogen, sulfur, and residual metals. Then, hydrocracking breaks down the carbon chain lengths. Subsequent isomerization rearranges the structure to yield lighter hydrocarbons suited for aviation. A fraction of this product is then isomerized and cracked to branched paraffins to reduce its freezing point. Also, note that although the presence of the oxygen atom in biofuels slightly reduces their energy content, its presence in the fuel molecular structure can actually reduce soot formation and emission. Before use, the biojet fuel is blended with the conventional jet fuel in equal amounts to incorporate the needed aromatics for sealing.

Hydro-processing of oil is already mature and at an early industrial stage and has recently achieved its approval for aviation, when blended 50/50 by volume with conventional Jet A fuel [13]. Both the FT and HRJ processes produce mainly n- and iso-paraffins and do not have the spread of heavier compounds seen in the conventional aviation fuel. Thus, without the addition of some heavier compounds biojet fuels fall on the lower end of the density limit for aviation fuels. This, along with aromatic content, is the reason that the normal convention is to blend the biojet fuel 50/50 by volume with the conventional petrojet fuel.

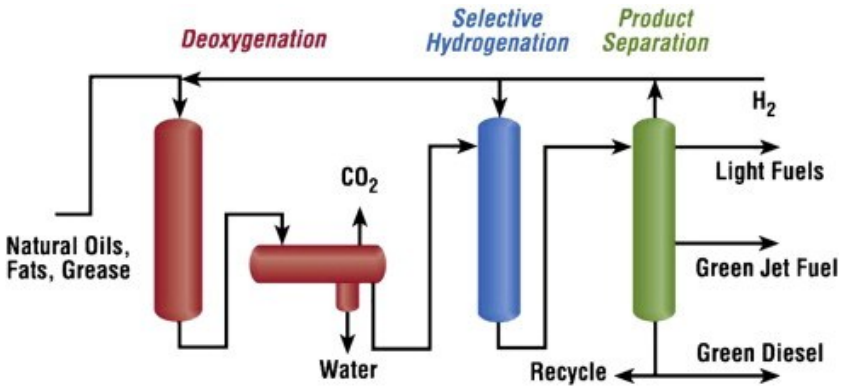

Figure 3. HRJ Production Pathway [24]

1.2 Aircraft Emissions

It is well recognized that the existence and operation of an airport has a potentially significant impact on the environment and health of people living or working in its vicinity in terms of related air pollutant emissions. The potential impact of airport operation on local air quality can be divided into three major sources: (1) aircraft engine emissions during standard taxiing, landing and takeoff activities, (2) aircraft auxiliary power units (APUs) used to provide power at the gate and start the main engines, and (3) ground service vehicles used in airport operations [25]. Ideally during combustion of a hydrocarbon-based fuel, the fuel goes through complete combustion producing only of carbon dioxide and water vapor. However, this never happens as you would need to eliminate all side chemistry and require the exactly correct, stoichiometric, amount of oxygen [14]. In application, combustion, entropy, and chemistry cause a large spectrum of exhaust species. Specifically, dissociation and chemical equilibrium cause partial products of combustion to appear even in cases of excess oxygen. This is inevitable and cannot be avoided. Thus, combustion sources can emit a range of air pollutants as by-products of the combustion process, including oxides of nitrogen (NO_x), carbon monoxide (CO), sulfur oxides (SO_x), particulate matter (PM), volatile organic compounds (VOCs), and the greenhouse

gas (GHG) carbon dioxide (CO_2). In the United States, the aviation sector is responsible for about 11% of the total transportation greenhouse gas emissions [21]. Emissions from commercial aircraft constitute 3.5% of total U.S. annual greenhouse gas emissions [2]. While CO_2 emissions are likely important for estimating global climate change impacts, a recent report on the climate change potential suggest that emissions other than CO_2, including soot and NO_x, also need to be included in forecast of potential aviation induced global climate change [26].

The potential impact of airport operations on local air quality is mainly due to aircraft activities on the ground, categorized as modes within the landing – takeoff cycle (LTO) by the International Civil Aviation Organization (ICAO) [18]. The ICAO maintains a databank of engine certification data for commercial aviation based on a standard LTO cycle. This cycle can be seen below in Table 3. The LTO cycle is intended to simulate aircraft engine operations that affect local air quality, specifically aircraft operations below 3000 feet altitude [17]. Most commonly, aircraft emissions are expressed as an emission index (EI) as grams of pollutants per kilogram of fuel burned. Expressing emissions in this way has the advantage of being consistent with reported emissions indices in the ICAO emissions databank [27]. The factors that control total emissions the airport air-shed receives from the operation of a single aircraft are the fuel flow rate and the emission index representative of a particular engine state (idle, climb-out, take-off, etc.), along with the time spent in that state [28].

Table 3. LTO Cycle Standards

Mode	Power (%)	Time in Mode (min)
Idle/Taxi	7	26
Approach	30	4
Climb-out	85	2.2
Take-off	100	0.7

Of primary environmental interest in considering alternatives to fossil fuel sources is on reducing the "carbon-footprint", i.e. the CO_2 emissions, from aviation. Due to similar hydrogen:carbon ratios, the amounts of CO_2 formed during combustion of petroleum and synthetic fuels will be similar [26]. However, the combined environmental impacts of the combustion of alternative fuels must take into account both life cycle CO_2 emissions and differences in emission performance. Because of the compositional differences, non-CO_2 emissions from aviation engines may also be significantly affected when alternative fuels are consumed. Many studies have been conducted to determine how alternative biojet fuels will affect the performance and emissions from gas turbine engines, but not all of their data concur with each other. As a rule-of-thumb, combustion efficiency generally increases with power setting due to the increased combustion temperature and pressure. The standard trend for conventional aviation fuel is that with an increase in power the emission index (EI) for carbon monoxide (CO) and total unburned hydrocarbons (UHC) decreases, while the NO_x emissions increase [26]. Thus, increasing power condition increases the combustion pressure and temperature causing CO and HC to decrease with engine thrust while NO_x increases with thrust.

It is also noted that NO dominates total NO_x at high power conditions, but NO_2 does make an important contribution at idle.

Nitrogen oxide compounds, primarily NO and NO_2 (their sum is often termed NO_x) are formed through the reaction of atmospheric nitrogen (N_2) and oxygen (O_2) during the combustion of fuel [14]. High temperatures from the combustor flame promote dissociation which produces NO and NO_2. These compounds are precursors for the formation of ground-level ozone, which can cause lung irritation and aggravate many conditions, including chronic bronchitis and asthma [29]. Nitrogen oxides contribute to smog, are injurious to plants and animals, and can adversely affect human health. Furthermore, nitrogen oxides emitted into the air can also convert to nitric acid, more commonly known as acid rain, and increase acid deposition.

Carbon monoxide forms from the incomplete combustion of any carbonaceous fuel where there is an oxygen deficiency [14]. This deficiency is usually found in fuel-rich combustor zones, although dissociation ensures that there are still significant CO levels even with lean mixtures. It is a pre-cursor to the formation of ground-level ozone and can cause harmful health effects by reducing the oxygen delivery to the body's organs [30]. It has been demonstrated that CO emissions are significantly dependent on fuel aromatics content, with heavier aromatics showing more effect [18]. Increasing aromatics and molecular weight of the fuel reduces combustion efficiency, thus CO increases.

Aviation fuels contain a complex mixture of hydrocarbon (HC) compounds, of which some portion remain unburned and are emitted in the exhaust. HC formation functions much like CO with aromatics and higher molecular weights decreasing combustion efficiency and increasing HC emissions [14]. After a hydrocarbon has been partially oxidized into a smaller

compound, further oxidation reactions may cease due to sudden decreases in temperature or oxygen concentration, resulting in a variety of partially oxidized hydrocarbons. These hydrocarbon compounds include a broad range of volatile organic compounds (VOCs) that survived combustion, including alkynes, alkenes, and alkanes. Not all these compounds are equal from the standpoint of public health though. For example, formaldehyde and benzene are both known carcinogens that make up a significant portion of the emissions and other VOCs are precursors to the formation of ground-level ozone and photochemical smog [31].

Sulfur oxides form from the sulfur present in the fuel composition during combustion [32]. These compounds can cause an array of adverse respiratory issues as well as lead to the formation of sulfuric acid, which leads to acid rain that deteriorates infrastructure and the environment [30]. Carbon dioxide is a natural product of complete combustion and cannot be avoided, although their life cycle fuel emissions can be reduced. CO_2 emissions from airports are not a direct health concern, but should not be ignored due to their influence on global warming.

Many studies have investigated the effect of alternative fuels on engine performance and exhaust emissions. These studies have shown that alternative fuels, when blended 50/50 by volume with conventional petrojet fuel, can satisfy the fuel specifications with acceptable Fit-For-Purpose characteristics [33]. Biofuels result in markedly higher thermal efficiencies than Jet A. Higher thermal efficiencies with neat biofuels may be attributed to lower equivalence ratios, leaner fuel/air mixtures, and consequently more complete combustion, due to the presence of extra oxygen in the biofuel [34]. Alternative fuels also have lower aromatics and thus higher H:C ratios than standard aviation fuel [1]. Also, their low aromatic, olefinic, and long-chain hydrocarbon content lead them to have a lower specific gravity than standard aviation fuel. HRJ fuels have shown the greatest reduction of both mass and number particulate matter emissions,

with an 80-90% reduction at idle when running neat HRJ and intermediate reductions when running blends [35]. Comparing NO_x results between studies is difficult because they must be corrected to ambient humidity and temperature to evaluate differences, but in general when running on neat FT fuels reductions of up to 12% have been achieved [18]. NO_x reductions come from the cooler flame temperature due to the larger chemical structures in the fuels.

Unburned hydrocarbon emissions vary substantially due to engine-to-engine variability and ambient conditions, but the majority of tests showed a significant reduction of unburnt HC when burning HRJ fuels with no discernable differences in engine performance, such as fuel flow rate or power output [35]. Fischer-Tropsch fuels have been found to reduce both carbon monoxide and unburned hydrocarbon emissions significantly at low power settings, although a large variation has been observed at higher throttle settings. CO reductions are seen due to the overall lower carbon content in alternative fuels. UHC emissions are greatly reduced because of the reduction in the aromatic content, which decreases soot formation, and the extra oxygen molecule that increases combustion efficiency [35, 18]. CO reductions of up to almost 20% over conventional fuel have been observed, although some contradictory results have also been found [1]. Overall, the major problem found thus far with the alternative aviation fuels is that their low aromatic content causes the fuel system seals to shrink, thus resulting in fuel leakage. When blended 50/50 by volume with conventional aviation fuel, the aromatic content is enough to prevent this seal shrinkage. Therefore, these fuels can be used with no penalty on engine performance and some reductions of emitted pollutants.

1.3 Summary of Objective

This research is motivated by two principles: (1) assuring energy availability and efficiency is central to the growth of aeronautics, and (2) the environment must be protected while sustaining growth in air transportation. The University of Kansas Biofuels "Feedstock to Tailpipe" Initiative is a multidisciplinary research team including scientists from chemical, mechanical, and environmental engineering, as well as ecology and evolutionary biology. The overall goal of the initiative is to advance the viability of producing next generation liquid transportation fuels from renewable feedstocks, including algae. The Alternative Fuel Assessment project's objective is to gain a better understanding of biofuels impact on aircraft engine performance and their emissions of nitrogen oxides and other criteria air pollutants. This research is critically needed at this time. Several major announcements have indicated a significant federal and commercial push for renewable aviation fuels in the coming years, and the state of Kansas, with its existing leadership in the industry, should invest now to further spur economic growth.

One of the major concerns with respect to renewable fuel use in jet aircrafts are how these fuels will affect engine operation, performance and emissions. The purpose of this work is to begin collecting data on the effect of renewable fuel blending with Jet A on engine combustion and to develop a consistent set of metrics for assessing algal based jet fuels once they are available for full scale combustion studies. Aviation emissions are an area of research that the University of Kansas has not been highly involved with in the past; therefore, one of the first requirements of this project is to establish a consistent and accurate method of emission sampling. Our combustion assessment will focus on two areas: engine performance during combustion and emissions for EPA criteria pollutants (CO, and NO_2) along with CO_2, NO, and

hydrocarbons. Large engine testing was conducted at the KSU Aviation Program facilities in Salina, KS. These tests used a PT6 turbopropeller engine, which produces about 600 shaft horsepower. The PT6 family of gas turbine engines is particularly well known for their extremely high reliability, with the mean time between overhauls on the order of 9000 hours in some models. Emissions analysis will focus on the EPA criteria pollutants, CO_2, and any affect the alternative fuels have on their concentrations.

This research is needed at this time to provide a baseline for future work. As mentioned previously, aviation emission sampling is a new field of study for the University of Kansas. Therefore, there is no set methodology or reference data to guide this investigation. The long-term goal is to produce alternative aviation fuel from algal feedstocks in-house and it would be useful to have conventional background emission data as a reference. Also, when this point is reached it will be useful to have a way to sample small batches of these alternative blends. Most emission sampling studies are very large, multi-team, expensive sampling studies that occur infrequently. Our goal is to have a quick small-scale set procedure in place to allow easy and often emission sampling of future blends. This will allow our chemical engineers information about their latest fuel and how the chemical composition is affecting engine performance and emission concentrations.

2. Methods and Materials

2.1 Optical Instrumentation

Instruments for ultraviolet (UV) and infrared (IR) spectroscopy have enough features in common with those designed for the visible region that they are commonly called optical instruments despite the fact that the human eye is sensitive to neither UV or IR wavelengths [36]. Optical spectroscopic methods are based upon six phenomena: (1) absorption, (2) fluorescence, (3) phosphorescence, (4) scattering, (5) emission, and (6) chemiluminescence. While the instruments for measuring each differ somewhat in configuration, most of their basic components are the same regardless of whether they are applied to UV, IR, or the visible portion of the spectrum. Typical spectroscopic instruments contain five components, including: (1) a stable source of radiant energy, (2) a transparent container for holding the sample, (3) a device that isolates a restricted region of the spectrum for measurement, (4) a radiation detector, which converts radiant energy to a usable signal, and (5) a signal processor and readout, which displays the transduced signal on a meter scale. Components (3), (4), and (5) are arranged in the same way for each type of instrument. The instrumental configurations used for the measurement of absorption, fluorescence, phosphorescence, and scattering require an external source of radiant energy. For absorption, the beam from the source passes though the sample directly into the wavelength selector. For the other three, the source induces the sample to emit characteristic fluorescence, phosphorescence, or scattered radiation, which is usually measured at a 90 degree angle from the source. Emission spectroscopy and chemiluminescence spectroscopy differ from the other types in the respect that no external radiation source is required; the sample itself is the emitter.

2.2 Semtech-DS (Sensors Emission TECHnology)

Engine exhaust emission sampling was performed using the Semtech-DS portable gaseous emissions analyzer, designed and built by Sensors Inc. They are one of the world's leading suppliers of in-use emissions test systems [37]. The Semtech-DS analyzer is primarily intended for on-vehicle emission monitoring of diesel and gasoline powered vehicles, and agricultural and construction equipment [38]. The analyzer can also be used for emissions monitoring in other mobile applications such as marine and mining, and also stationary applications such as engine test cells. The focus of this paper is on the stationary applications of the Semtech-DS unit with a gas turbine aircraft engine on a test stand. Kerosene is the fuel used in gas turbine engines, which is not a liquid fuel type that the Semtech-DS was necessarily designed for. The Semtech-DS can still be used for kerosene analysis, but with some small manipulations.

The Semtech-DS product line is based on a number of modular, stand-alone measurement subsystems [38]. The following is a list of measurement subsystems included in the Semtech-DS emission analyzer.

- Heated Flame Ionization Detector (FID) used for total hydrocarbon (THC) measurements
- Non-Dispersive Ultraviolet (NDUV) used for nitric oxide (NO) and nitrogen dioxide (NO_2) measurements
- Non-Dispersive Infrared (NDIR) used for carbon monoxide (CO) and carbon dioxide (CO_2) measurements
- Electrochemical Sensor used for oxygen (O_2) measurements

These subsystems' methods provide direct comparison to test cell measurements for THC, CO, CO_2, NO and NO_2 in compliance with CFR-40, 1065 subpart J [38]. Sensors Inc. states that all

the subsystems of the Semtech-DS have been designed to match the performance of laboratory instrumentation.

Figure 4. Semtech-DS

2.2.1 NDUV

The measurement of nitric oxide (NO) and nitrogen dioxide (NO_2) from the exhaust gases are done by using a proprietary non-dispersive ultraviolet (NDUV) analyzer, a type of ultraviolet absorption spectroscopic quantitative detection method. This type of analyzer uses the fact that each type of compound will absorb UV radiation in its own characteristic "fingerprint" pattern [36]. A light-emitting diode (LED) emits UV energy which passes through a beam-splitter to provide multiple wavelengths. The multiple wavelengths then reflect off two mirrors and recombine at the beam-splitter. When the beams are recombined some wavelengths recombine constructively and some destructively, which creates an interference pattern. This

interference pattern then goes through the sample where some wavelengths are absorbed and some are transmitted. The transmitted portion reaches the detector, which reads information about every wavelength simultaneously. To obtain the UV spectrum, the detector signal is sent to the computer where an algorithm is performed to convert the detector signal into a single beam spectrum. This algorithm has some minimum value limits that caused sampling difficulties that will be discussed later. A reference beam is also collected without a sample and the sample beam is ratioed to the background beam to produce a transmittance spectrum. This transmittance spectrum can then be converted into an absorbance spectrum. This "fingerprint" absorption pattern is then correlated with a concentration of the pollutant of interest.

Prior to analysis in the NDUV analyzer, the exhaust sample is dried with an ambient temperature coalescing filter followed by a thermoelectric chiller [38]. This will remove the heavy hydrocarbons that would otherwise condense on the optics. It also removes water vapor, which causes interference and can condense on the sample cells. To chill the sample gas, a thermoelectric chiller capable of cooling a continuous exhaust sample to 30°C below ambient, is integrated in the sampling system. The sudden temperature drop effectively eliminates all the hydrocarbons that can contaminate the sample cell windows and reduce the water vapor concentration to 1-2-% (vol). Prior to the chiller, the sample is pre-cooled to ambient temperature and passed through a coalescing filter, where the bulk of the water is removed. There will be a small amount of NO_2 that is lost in the drying process, but this loss is in the acceptable range. The NDUV analyzer can report constant measurement for NO and NO_2 at a rate of 4Hz to the Semtech-DS unit. The system has been shown to be comparable to a laboratory chemiluminescent analyzer.

2.2.2 NDIR

A non-dispersive infrared Automotive Micro-Bench II (AMBII) analyzer, which is an infrared absorption spectroscopic quantitative detection method, is used for the measurement of carbon monoxide (CO) and carbon dioxide (CO_2) exhaust elements. The NDIR functions much the same as the NDUV, with IR radiation being absorbed by a sample and correlated to a "fingerprint" absorption pattern with the concentration of the pollutant of interest. Again, the exhaust must be first dried through a coalescing filter and then a thermoelectric chiller. This removes any water vapor that would otherwise cause interference in the infrared channels. The NDIR AMBII analyzer is housed in a temperature controlled enclosure for maximum stability in rapidly changing thermal environments [38]. The NDIR sends concentration measurements on a continuous 0.833Hz or 1.2 second period data rate to the Semtech-DS. The range for CO is 0-8%, with the range for a typical exhaust around 1000 ppm or 0.1%. When high end span calibrated in the range of 1200 – 1500 ppm the NDIR analyzer has an accuracy of 50 ppm for CO. Overall, this is comparable to the equipment found in an emission testing laboratory.

2.2.3 FID

Flame Ionization Detection (FID) is a gas chromatographic (GC) quantitative detection method where the column effluent is burned in an air-hydrogen flame. Voltage is applied across the flame, resulting in a measurable current [38]. Organic compounds produce ions and electrons as they burn, which increases the current across the detector. This method responds to all compounds containing organic carbon with good sensitivity. The exhaust gas is transported to the analyzer via a heated sample line. This heated sample line is designed to minimize the loss of hydrocarbons from the exhaust sample before it reaches the analyzer. For this reason, the

Semtech-DS system maintains the exhaust sample in the heated line at 191°C so there is no condensation. The heated line is made of Teflon that is wrapped with a heater and molded inside a larger insulated flexible tube with a durable outer skin. After the heated sample line and heated filter, a fraction of the sampled exhaust gas is routed through the stainless steel heated FID chamber for measurement. All aspects, including internal parameters such as fuel flow rates and pressures, of the total hydrocarbon FID analyzer are electronically controlled and monitored by the Semtech-DS embedded control software. The THC FID analyzer fuel consists of a 40/60 blend of hydrogen/helium. The fuel cylinder is housed completely inside the Semtech-DS chassis, and includes an electronic pressure sensor connected to the data acquisition system that allows the user to monitor the fuel capacity from the SENSOR Tech-PC software application. These bottles hold 105 compressed liters and will last for approximately 8 hours of run time for the Semtech-DS analyzer.

2.2.4 Electrochemical Sensor

The electrochemical sensor monitors the oxygen level of the sample exhaust by using an oxygen sensor cartridge. This cartridge is replaceable, as they do wear down over time. The exhaust sample flows through the analyzer and the sensor produces a signal that is proportional to the partial pressure of oxygen in the exhaust gas [38]. Then the AMBII module processes the signal and reports the results to the Semtech-DS.

2.2.5 Calibration Information

Before each testing session the Semtech-DS analyzer must be calibrated for each pollutant of interest to be tested. To calibrate the Semtech-DS the analyzer must be turned on, connected to the Sensors Tech PC software and allowed to warm-up for 60-90 minutes, to allow

the FID analyzer to reach 190°C needed for span calibration. Once the FID is ready, the Semtech-DS can be calibrated. This calibration is accomplished by establishing low and high concentration reference points. The low value comes from sampling the ambient air and setting that as the zero point. The high value comes from gas calibration bottles of know concentration chosen to exceed the expected concentration range of the pollutants to be sampled. This calibration is checked for accuracy by running audit bottles of known concentration through the Semtech-DS. Once the audit is passed the analyzers are ready for sample collection.

2.3 Baseline Testing

Initial testing with the Olympus HP ES turbine engine was intended to be a training experience to become accustomed to calibrating and operating the Semtech-DS unit. The Olympus HP ES was to be used as our pilot-scale engine, with the idea that in the long-term we could compare any pilot-scale data to the full-scale tests on the PT6 to see how they scaled up and compared. The Semtech-DS unit had never been used in applications such as these and knowledge of how it performed during these tests was desirable.

2.3.1 Location

The Olympus HP tests for this project were conducted in the Mal Harned Propulsion Laboratory of the University of Kansas. The facility is located in a hangar at the Lawrence Municipal Airport. The hanger is 3,480 square feet, with the test cell located inside the hangar. The test cell was designed to handle many types of engines such as: turbojet, turbofan, turboprop, reciprocating engines, and some small test rockets. The test cell is constructed of concrete with dimensions 12 feet wide by 24 feet long by 10.5 feet tall and can be opened to the environment. Any engine to be tested in the Mal Harned Propulsion lab test cell must be

compatible, or made compatible, with the test stand in place. This test stand was designed to support the Thielert Centurion 1.7/2.0 turbo diesel and the Innodyn 165TE turboprop. The test stand uses steel plates to be compatible with the Innodyn, but from these plates more engines can be tested. The control panel for the testing area and engine operation are located in an adjacent room to the test cell to ensure the safety of the people involved. The control panel is made up of a throttle, compact engine display (CED), starter switches, and the Full Authority Digital Engine Control (FADEC) panel. The throttle is operated by a percent power, otherwise by RPM control throttles. The throttle goes from 0% power to 100% power. The CED unit shows the engine safety parameters: load, oil temperature, oil pressure, water temperature, and gearbox temperature. The FADEC is used to test the engine's systems and gives warnings for those systems.

Figure 5. Mal Harned Test Stand

2.3.2 Olympus HP

The engine used for baseline testing was an Olympus HP electric start turbojet that runs on kerosene mixed with 4.5% Aeroshell lubricating oil. It comes from Advanced Micro Turbines (AMT) company in the Netherlands and operates with a single radial compressor and an axial flow turbine [39]. The Olympus HP ES provides a thrust of 230 Newton at 108,000 RPM. The combustion chamber is of the annular type, which is fitted with a unique “low pressure” fuel system, developed by AMT Netherlands. The turbine is protected from misuse and accidental damage by means of a microprocessor based controller, an electric control unit (ECU), which

regulates the maximum performance within pre-programmed software limits. The ECU is fully automatic and needs no adjustment by the operator. The Olympus HP is compatible with three fuel types: (1) kerosene or JP-4 fuel that is used in military applications, (2) paraffin fuel that is mostly used in oil stove applications, and (3) Jet A fuel that is used in commercial aviation. The Olympus HP ES also uses the fuel for lubrication, so the fuel must be pre-mixed with 4.5% Aeroshell 500 turbine oil before use. This oil takes care of the lubrication during start-up and power-down sequences.

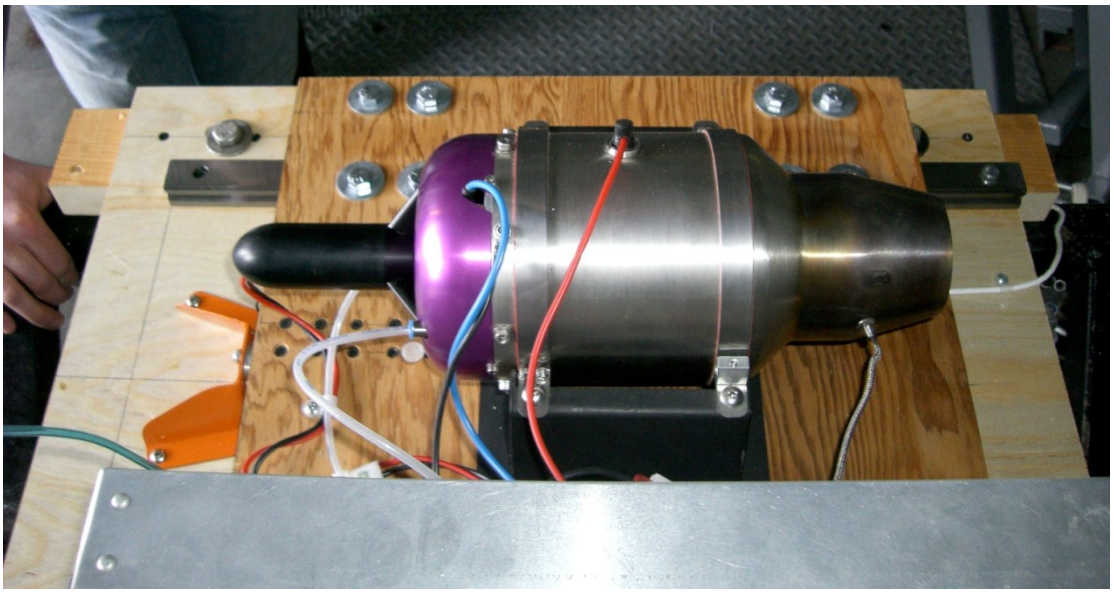

Figure 6. Olympus HP

2.3.3 Olympus HP Testing Issues

Baseline testing with the Olympus HP ES turbine engine quickly ran into difficulties. After calibrating and running one set of tests we discovered that the Semtech-DS unit was not providing viable nitric oxide (NO) data, and was instead reporting negative emissions. This was not to be expected and seemed highly unlikely. Our first plan-of-action was to move the Semtech-DS probe further downstream from the Olympus HP engine. Initially the probe was

placed directly behind the exhaust plume downstream 1 meter. Due to space limitations of the testing facility, we could only move the probe back another meter, to a distance downstream of 2 meters from the Olympus engine. This further dilution did show an effect on our emission data, but did not improve our NO values.

After further investigation into our NO issue and through communications with Sensors-Inc., the manufacturer of the Semtech-DS, the problem seemed to be caused by an excess of hydrocarbons interfering with the NDUV analyzer. The Semtech-DS module was designed to sample emissions from diesel fuels; it was not designed to handle kerosene exhaust. Kerosene, and especially jet fuels, has additional additives that contribute a heavy hydrocarbon concentration. Also, the Olympus HP being a pilot-scale engine does not provide a great deal of load on the engine, which would cause the fuel to more completely combust. In addition, the 4.5% Aeroshell oil that must be mixed with the fuel to operate the Olympus HP further increases the heavy hydrocarbons the Semtech-DS must analyze. All of these factors lead to total hydrocarbon (THC) levels exceeding 1,100 ppmC. The technicians at Sensors Inc. believed that if we could add some load to the engine and get the THC values in the 200 – 300ppmC range that our NO values should be viable and accurate. Unfortunately, our set-up at Mal Harned Propulsion Laboratory did not allow us to increase the Olympus HP load. However, we did perform a couple tests using only half the normal 4.5% Aeroshell lubricating oil amount, but that did not provide a sufficient reduction in THC concentrations.

An additional remedy to our NO issue was offered by the Sensors-Inc. technicians; one of employing a second-stage carbon filter to scrub out the hydrocarbons. The use of the second-stage filter would complicate the testing procedure slightly. First, we would have to attach the second-stage filter and run a test. The filter should scrub out everything expect NO, thus

eliminating the hydrocarbons causing the interference to the NDUV analyzer along with NO_2 compounds in the gas sample. After a test with the filter attached, the filter would need to be removed and another test would need to be ran to provide data on the emissions of NO_2. Upon running some tests with the second-stage carbon filter attached, we saw varying results. During the first test, the filter seemed to be functioning properly. NO_2 values were practically zero and for the first time NO values being collected were positive. Upon testing the filter an additional time, there was no reduction in any of the emissions of interest and the NO values were once again negative. The filter was supposed to last for 6-8 hours and with our testing only lasting less than 2 hours a test, the filter should have had plenty of capacity remaining. Analyzing the data, it would seem that the filter became saturated quicker than expected due to our extreme level of hydrocarbon emissions.

Additional tests on the Olympus HP with the second-stage filter to determine if it would resolve our NO issues were not performed. The Semtech-DS is sensitive to high levels of hydrocarbons as previously mentioned, and there were reasons to believe, from other research projects' testing using the Semtech-DS, that there could be the possibility of damage to the NDUV sensors from residual build-up of NO_x and high levels of hydrocarbons. Therefore, testing at Mal Harned Propulsion Laboratory for this study was terminated. The Olympus HP engine was not a viable engine choice for functioning with our current equipment, but testing did continue on the PT6 turboprop engine at Kansas State University's Salina Aviation facility.

2.4 Probe Development

Due to the limitations of our testing capabilities at the Mal Harned lab and difficulties scheduling days to test at the Salina facility, no testing was performed during the winter of 2011-

2012. This time did offer us a chance to develop a probe housing manifold for the Semtech-DS probe. Housing for our sampling probe was needed to reduce vibration during sampling. The Semtech-DS probe is constructed out of a flexible material allowing the probe to have some movement. During sampling, the exhaust gases exiting the gas turbine engine travelled at relatively high velocities and caused the sampling probe to bounce during collection. A housing manifold was needed to reduce the vibration so that exhaust samples were only being collected from a single steady vertical plane of the exhaust plume.

Multiple probe designs were discussed; a 12 orifices probe and a 3 orifices probe were contemplated. These new probes would have allowed for collecting samples from multiple vertical planes simultaneously, allowing for a more wide-spread collection of the entire exhaust plume. Unfortunately, these designs would have been very labor and time intensive to design and construct. The design we were able to produce is not a new sampling system, but more of a case for the original sampling probe. This housing provides a solid enclosure that holds the probe in-place when sampling is being performed. The probe housing reduces the vibration of the probe in the exhaust plume, so that probe is constantly taking data only from a single plane in the exhaust plume. Stainless steel 303 was purchased from McMaster-Carr to machine into the probe enclosure. Stainless steel 303 was chosen because it should be non-reactive with the exhaust emissions, therefore not altering our data. Alan Walker, the C&PE lab technician machined the stainless steel 303 block to the dimensions of our probe enclosure, which were designed by Alex Karwas in AutoCAD.

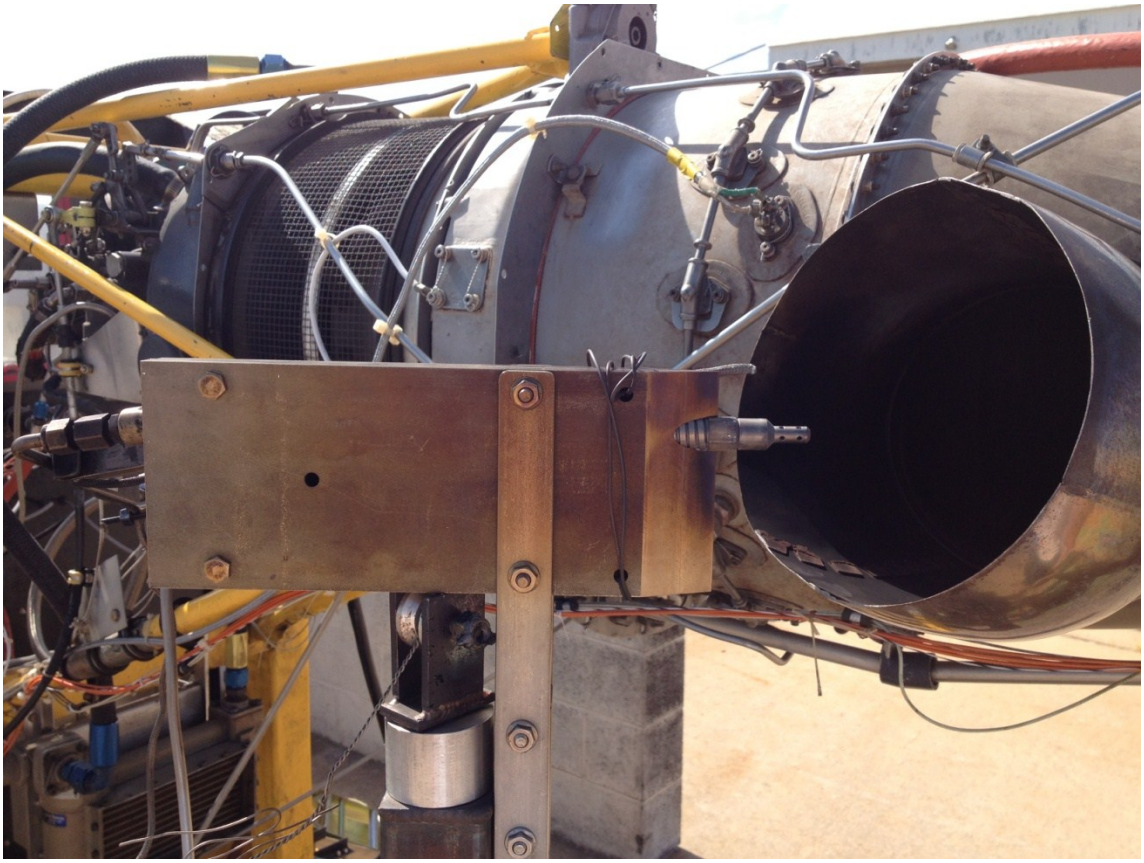

Figure 7. Probe Shield

2.5 Full Scale Testing

2.5.1 Location

Full scale testing was done at Kansas State University's Salina Aviation Center facility located in Salina, KS. The department our research worked with is located in a 33,000 ft^2 aviation center equipped with modern classrooms and computer labs [40]. Training equipment includes operable turbine engines, flyable piston engines, and complete flyable aircraft systems used in, inspections, repair, and replacement maintenance training. Testing conducted at this facility was done using a portable test stand. The test stand is placed in an outdoor test cell and strapped down to anchors in the concrete. The test cell is open to the environment.

Figure 8. KSU Salina Aviation Facilities

2.5.2 PT6

The PT6 turbopropeller, made by Pratt & Whitney Canada, produces about 600 shaft horsepower. The PT6 family of gas turbine engines is particularly well known for their extremely high reliability, with the mean time between overhauls on the order of 9,000 hours in some models. Due to this reason, the PT6 family has been a top selection in the commercial aviation fleet in the past and should give us comparable emission data to commercial aircraft currently in use.

Figure 9. PT6 on test stand in testing cell

2.5.3 Full Scale Testing

Full scale testing on the PT6 truboprop engine started on November 29th, 2011. This was our first testing trip to K-State Salina's facility and was intended to be a baseline run. Equipment for testing, including the Semtech-DS analyzer, gas calibration bottles, tools and supplies used to set-up the equipment, and any alternative fuel blends, was brought from the University of Kansas to Salina on test day. During our first trip, we ran two tests: one with Jet A commercial fuel and one with JP-4 military fuel. Both fuel runs were successful at collecting data with the Semtech-DS analyzer. We did encounter some minor issues: 1) the ambient temperature probe was placed

in an area where it was affected by the engine exhaust and 2) the nitric oxide data was still negative. Both of these issues were easily solved. The ambient temperature probe must be carefully placed in a location where the exhaust gas of the PT6 is not raising the temperature of the ambient air. Our nitric oxide issue was solved by testing with our second stage carbon filter attached to the Semtech-DS analyzer, as described previously. We were hoping to avoid having to test with the second stage filter on the PT6 because it is a full-scale engine with improved combustion over the Olympus HP pilot-scale engine. This first trip was useful for establishing a baseline testing procedure and becoming familiar with the testing set-up at Salina, but because there were some initial issues, the data collected from this trip was not used for later analysis.

Our second trip to KSU Salina's facilities was on July 10th, 2012. The long delay from the first trip to the second trip was a result of not being able to test in winter, other research projects needing to perform testing with the Semtech-DS analyzer during the spring semester, the Semtech-DS unit needing some maintenance work at the beginning of the summer, and conflicting travel arrangements between universities. During this second trip to Salina we were able to successfully gather both NO and NO_2 data from the PT6 engine. Two test runs were performed: one with Jet A without the carbon filter attached and one with Jet A with the carbon filter attached. Having to perform multiple test runs on the same fuel is repetitive but allows us to compare emission results of CO_2, CO, and THC to get an idea of the run-to-run variability of the engine.

The third testing trip to Salina was performed on September 12th, 2012. This testing trip was our first trip testing alternative blends. The three fuels tested were Jet A, a HRJ fuel blended 50/50 by volume with Jet A, and a Fischer-Tropsch fuel blended 50/50 by volume with Jet A. These alternative fuels used were obtained from the Air Force. The HRJ fuel was from a tallow

feedstock and the FT fuel was a Sasol IPK derived from coal. Both fuels are good representatives of their respective production process and are commonly used in the literature. Blending of the alternative fuels were conducted at the University of Kansas' Lawrence Municipal Airport hangar prior to the testing date and transported with the equipment on the day of testing. In total six test runs were performed, two for each fuel with one run for NO and one run for NO_2.

Our final testing date was October 24th, 2012. This testing date was used to perform the same tests as the prior trip in order to collect more data on the alternative blends and check the reproducibility of the alternative fuel data. The same fuel blends were tested and the same procedures were followed to replicate the third trip as closely as possible. The fuels were tested in the same order and as close as possible to the same duration as our third testing trip. Every attempt was made to as closely as possible to duplicate the third testing date.

2.5.3.1 Alternative Fuel Blending

Alternative fuel blending was conducted prior to the corresponding testing date at the University of Kansas' airport hanger located at Lawrence Municipal Airport. The two alternative fuels that were tested are a tallow HRJ fuel and a Fischer-Tropsch fuel acquired from the Air Force. The blending procedure that was used for this testing was also recommended by the Air Force. During blending, every precaution was taken to avoid cross-contamination between the FT and HRJ fuels. Each blend had its own mixing drum and transport drum. The blending equipment, pump, and transfer totes were rinsed between fuels and allowed to dry.

For each blend 10 gallons of Jet A was placed in the mixing drum followed by 10 gallons of alternative fuel and mixed for 25 minutes. After 25 minutes of mixing, the blend was pumped from the mixing drum to the 20 gallon transport drum for transport to Salina. The same pump

was used for both blends, but was heavily rinsed with Jet A fuel and allowed to dry before use. The only difference in the two blending dates, for trip three and trip four, was that for trip three the blending was done the day prior to testing while for trip four the blending was down two days prior to testing. Everything else remained the same for the two blending dates.

Figure 10. Alternative Fuel Blending

2.6 Data Analysis

2.6.1 Olympus HP Results

Analyses of the Olympus HP results were limited. The majority of this testing was just to establish familiarity with the Semtech-DS analyzer. Also contributing to the lack of data analysis

for this testing was the numerous issues that were encountered. Not all tests were calibrated correctly, rendering the data highly inaccurate for some runs. Further analysis also requires the fuel density and H:C ratio, which could not be calculated due to the unknown composition of the 4.5% Aeroshell lubricating oil that is added to the Olympus HP. For these reasons, Olympus HP data is only presented as the raw exhaust concentrations. These results are expressed in percentage of atmospheric concentration (%) of the exhaust plume, for CO_2, CO, and O_2. The remaining pollutants, NO, NO_2, NO_x, and THC, are expressed in parts per million (ppm) by volume. Once again, it must be emphasized that these results are raw data and have not be normalized to fuel use, but are strictly the readings directly from the exhaust plume of the Olympus HP turbojet engine collected by the Semtech-DS analyzer.

2.6.2 PT6 Data Analysis

Results for the PT6 data were analyzed in several ways. The raw data is still available and is the starting point for all further analysis of the data. However, the Semtech-DS analyzer has a post processing software program that can perform a variety of analysis for the user, if there is enough information. Unfortunately, our research was not able to take advantage of all these options due to the fact that, again, the Semtech-DS was not designed for sampling kerosene exhaust from gas turbine engines. The calculations that we were able to perform were ambient humidity and temperature corrections and fuel-specific emission calculations. The humidity correction factor, Kh, is applied to the raw instantaneous concentrations collected by the Semtech-DS. The correction factor is applied by the CFR40 §86 method [38]. This method is for gasoline and diesel engines, so it is not as accurate as possible, but more accurate than the otherwise raw concentrations.

Fuel specific emissions are the mass fractions of each pollutant in the fuel to the combusted air/fuel mixture. This fraction is readily computed directly from concentrations of the measured exhaust constituents. To express fuel-specific emissions in grams of pollutant per gram of fuel, the mole fraction of the pollutant to the fuel burned is computed. This is simply the ratio of the measured concentration of pollutant to the sum of the CO, HC, and CO_2 concentrations in the exhaust, which reflect the number of moles of the fuel that is consumed per mole of exhaust. The mass fraction of each pollutant to fuel burned is then computed by multiplying the mole fraction by the ratio of the molecular weights of the pollutant to the molecular weight of the fuel. Computing fuel specific emissions is useful for comparing pollutant concentrations between fuels, because now emissions concentrations are normalized to a specific quantity of fuel.

Using these fuel-specific emissions concentrations, plots of pollutant versus test run in minutes and also pollutant versus CO_2 concentration were prepared and can be found in the appendices. Pollutant versus run time plots show how the concentrations change with the throttle of the engine during our actual testing. Plotting pollutants versus CO_2 can be useful in observing trends in the pollutant concentrations. Plots versus CO_2 are performed because the concentration of CO_2 should be directly proportional to the amount of fuel being consumed and normalized emissions to CO_2 should reduce some of the variability of the engine.

3. Results

3.1 Olympus HP results

Baseline testing began in Mal Harned Propulsion Laboratory on May 3rd, 2011. These first testing session results were difficult to analyze. The results of the initial test running on Jet A fuel mixed with 4.5% Aeroshell lubricating oil with the probe stand placed 3 feet downstream of the Olympus HP exhaust nozzle can be seen below in Table 4. For this run the Semtech-DS was span calibrated as it had been prior to this work for diesel and locomotive sampling. As we learned, this was not the optimal way to calibrate the analyzer for our work. Therefore, we do not believe the data we collected during this first test run is a valid representation of actual emissions levels, but it did illustrate the issue that we would have testing further with this set-up and engine.

Table 4. Olympus HP Baseline Results

Baseline 5/3/2011 with probe at 3ft								
Throttle	**CO2 (%)**	**CO (%)**	**CO (ppm)**	**NO (ppm)**	**NO2 (ppm)**	**THC (ppmC)**	**O2 (%)**	**EGT (°C)**
Idle	0.95	0.0542	542.92	-22.88	4.046	955.26	19.601	162.85
Mid	0.55	0.063	630.08	-13.10	2.047	907.14	20.11	114.88
High	0.94	0.055	552.64	-28.45	5.553	923.14	19.6	163.32

During the second test, calibration was perform with parameters (gas calibration values, fuel specific gravity, and H:C ratio) better suiting kerosene fuel sampling. From our first sampling session we gathered general concentration values that allowed us to more accurately set high span calibration reference points during our second run. Also, more accurate chemical composition information was used during post processing analysis of the data, that reflecting

kerosene over diesel. Table 5 shows our results from the second testing performed on July 26th, 2011.

Table 5. Olympus HP Baseline2 Results

Baseline2 7/26/2011 with probe at 3 ft								
Throttle	**CO2 (%)**	**CO (%)**	**CO (ppm)**	**NO (ppm)**	**NO2 (ppm)**	**THC (ppmC)**	**O2 (%)**	**EGT (°C)**
Idle	0.4906	0.0521	521.55	-1.319	0.891	819.94	20.56	157.6
Mid	0.572	0.0372	372.52	-1.239	1.047	903.17	20.31	181.1
High	0.8008	0.0473	473.08	-1.242	0.958	898.40	20.02	234.0

The second baseline test shows carbon dioxide following the trend we would expect, but not other emissions. As the throttle is increased CO_2 should increase due to increased fuel flow, and thus consumption. Flame temperature increases as throttle is increased, as shown by the exhaust gas temperature (EGT) data which was collected from a thermocouple connected to the sampling probe. An increase in flame temperature should also increase combustion efficiency, thus decreasing carbon monoxide and hydrocarbon emissions, and increasing NO_x emissions due to the higher temperatures promoting dissociation of atmospheric nitrogen (N_2) and oxygen (O_2). The second test data does show signs of following these trends from the throttle increase of Idle to Mid throttle setting, but not from mid to High throttle setting increase.

During both of these first two baseline tests the nitric oxide values were never positive, despite proper calibration with our span gases. After communicating with Sensors Inc., the manufacturer of the Semtech-DS analyzer, we were informed that the Semtech-DS was not

designed for sampling exhaust gas with such high levels of hydrocarbons and relatively small levels of nitrogen oxides. Therefore, the Sensors' technicians believed that we were getting hydrocarbon interference of the NDUV optics and if we could bring the total hydrocarbon levels down below 300 ppmC we should see positive NO data. In an attempt to reduce our THC values over the next couple of testing dates, the probe stand was moved downstream of the exhaust nozzle another 3 feet, placing the sampling probe a total of 6 feet from the exhaust nozzle, and using only half the recommended amount of lubricating oil for the Olympus HP start-up and cool-down processes. These data sets can be seen below in Table 6 and Table 7, respectively.

Table 6. Olympus HP Half Lubricating Oil Results

Half Oil Blend 9/9/2011 with probe stand at 3 feet								
Throttle	**CO2 (%)**	**CO (%)**	**CO (ppm)**	**NO (ppm)**	**NO2 (ppm)**	**THC (ppmC)**	**O2 (%)**	**EGT (°C)**
Idle	0.473	0.0514	514.11	-10.350	3.613	701.80	20.62	146.9
Mid	0.530	0.0378	378.62	-18.085	5.064	745.25	20.52	167.9
Half Oil Blend 9/13/2011 with probe stand at 6 feet								
Run Time	**CO2 (%)**	**CO (%)**	**CO (ppm)**	**NO (ppm)**	**NO2 (ppm)**	**THC (ppmC)**	**O2 (%)**	**EGT (°C)**
Idle	0.133	0.0131	131.60	-3.086	1.560	152.86	20.71	52.47
Mid	0.306	0.0208	208.68	-9.277	3.136	421.42	20.9	97.18
High	0.371	0.0224	224.39	-13.63	4.461	435.69	20.89	109.92

There was no significant reduction in THC levels due to the reduction in 4.5% Aeroshell lubricating oil; THC values were reduced by only 16% compared to previous data collected. Further reductions in sampled THC values were seen by moving the sampling probe downfield

due to allowing more dilution with the ambient air to take place. An average reduction of 75% was seen at Idle throttle and 44% reduction at Mid throttle levels were observed over the half lubricating oil blends. These results displayed that the higher throttle settings of the half oil blend actually showed increased THC levels relative to the normal blend when the probe stand was placed 6 feet from the engine.

Table 7. Olympus HP Downfield Results

Standard Jet A Blend 9/13/2011 with probe stand at 6ft								
Throttle	**CO2 (%)**	**CO (%)**	**CO (ppm)**	**NO (ppm)**	**NO2 (ppm)**	**THC (ppmC)**	**O2 (%)**	**EGT (°C)**
Idle	0.183181	0.019433	194.3255	-6.6954	4.152903	175.0542	21.09374	58.7886
Mid	0.323089	0.024352	243.5075	-11.016	5.396667	405.5411	20.9	97.8826
High	0.375277	0.025443	254.4197	-14.38	6.106154	426.8554	20.87077	109.566
Half Oil Blend 9/13/2011 with probe stand at 6ft								
Throttle	**CO2 (%)**	**CO (%)**	**CO (ppm)**	**NO (ppm)**	**NO2 (ppm)**	**THC (ppmC)**	**O2 (%)**	**EGT (°C)**
Idle	0.13383	0.013157	131.6001	-3.0869	1.56087	152.8604	20.71878	52.4730
Mid	0.306964	0.020869	208.689	-9.2776	3.136	421.4204	20.9	97.1809
High	0.3717	0.022439	224.3905	-13.637	4.461111	435.69	20.891	109.927

Unfortunately, none of these remedies corrected our NO measurement issue. Even when THC values were below 300 ppmC NO values remained negative. At this point communications with Sensors' technicians began again. After they took a look at our data sets, they determined that the most likely solution to our problem would be to employ the use of a second stage carbon filter that attaches to the Semtech-DS unit. The second stage carbon filter attaches to the back of the Semtech-DS analyzer via an access port. This attachment re-routes the exhaust gas sample

portion destined for the NDUV analyzer, first through the scrubber where all hydrocarbons and NO_2 will be removed, then back to the NDUV where it can now be analyzed for NO without any interference. This does not alter any of the other subsystem analyzers of the Semtech-DS that seem to be functioning properly. This set-up requires two runs to collect samples of all our pollutants of interest, one for NO data and the other for NO_2 data. We can, however, compare the reproducibility of runs by comparing the emission data of the non-nitrogen containing pollutants that should not be affected by the second stage carbon filter scrubber.

Table 8. Olympus HP Carbon Filter Results

Carbon Filter1 Added Filter 3/27/2012 with probe at 3 ft							
Throttle	**CO2 (%)**	**CO (%)**	**CO (ppm)**	**NO (ppm)**	**NO2 (ppm)**	**THC (ppmC)**	**O2 (%)**
Idle	0.701806	0.092254	922.5139	0.274194	-1.25935	1134.519	20.34516
Mid	0.812718	0.050003	500.0325	0.689091	-1.39	1061.748	20.15155
High	1.154392	0.062946	629.4672	3.008	-1.336	1133.55	19.70664
Carbon Filter1 No Filter 3/27/2012 with probe at 3 ft							
Throttle	**CO2 (%)**	**CO (%)**	**CO (ppm)**	**NO (ppm)**	**NO2 (ppm)**	**THC (ppmC)**	**O2 (%)**
Idle	0.763235	0.094336	943.3506	-13.4006	4.82	1085.332	20.3
Mid	0.840493	0.060276	602.7912	-20.9229	5.367857	1065.643	20.2
High	1.198384	0.076368	763.6805	-32	6.4016	1119.711	19.68328

As Table 8 shows, the values for CO_2, CO, and THC of the two runs follow the same trends and are within an acceptable range of each other, thus showing good reproducibility of the data from one run to the next. CO_2 values from the two runs never showed more than 10%

variation, with an average throttle variation of just 5.3%. This data set shows good signs that the second stage carbon filter would allow us to accurately collect NO_x data. The filter is supposed to have an 8-hour run lifetime, so we decided to attempt a second run using the same filter since our first run with the carbon filter attached did not take more than 2 hours. The second run did not show the same signs as the first run. In fact, the NO values were again negative during the second run with the carbon filter.

Looking at the data, we concluded that the carbon filter became saturated much quicker than expected due to the heavy hydrocarbons present in our exhaust and began leaching pollutants back into the sample stream causing our data sample to be unusable. It does, however, appear that employing a second stage carbon filter for one use only would provide us with the capability to collect the desired emissions during our full-scale testing of the PT6 turboprop engine at KSU Salina's facilities. At this time testing with the Olympus HP engine was finished. Table 9 shows the most accurate collected emissions data for the Olympus HP turbojet pilot-scale engine.

Table 9. Average Olympus HP Carbon Filter Results

Carbon Filter1 averages with probe stand at 3 ft							
Throttle	**CO2 (%)**	**CO (%)**	**CO (ppm)**	**NO (ppm)**	**NO2 (ppm)**	**THC (ppmC)**	**O2 (%)**
Idle	0.7325209	0.093295	932.9322	0.274194	4.82	1109.926	20.32258
Mid	0.8266055	0.05514	551.4118	0.689091	5.367857	1063.696	20.17577
High	1.176388	0.069657	696.5739	3.008	6.4016	1126.631	19.69496

3.2 PT6 Results

3.2.1 Jet A Fuel

Jet A fuel emission concentrations were gathered on every trip to Salina. This made it the only fuel that was tested during every trip and therefore usable as reference baseline data. This is useful because even under similar testing conditions (duration, fuel, temperature, humidity, wind, etc.) there is expected to be some run-to-run variability of the engine, reported in the literature as typically better than 10% [31]. During our first trip to Salina testing was conducted mainly to become familiar with the testing set-up, calibration, and procedure for the PT6 engine. The Jet A data from our initial PT6 testing (expressed as fuel-specific emissions in grams of pollutant per kilogram of fuel burned) can be seen below in Table 10.

Table 10. Jet A results from first round of testing

Salina1 Jet A NCF 11/29/2011								
Throttle	Fuel Specific CO2	Fuel Specific CO	Corrected Fuel Specific NO	Corrected Fuel Specific NO2	Corrected Fuel Specific NOx	Fuel Specific HC	Fuel Specific O2	EGT
	g/kg fuel	g/kg fuel	g/kg fuel	g/kg fuel	g/kg fuel	g/kg fuel	g/kg fuel	deg C
Idle	3028.228	59.7284	n/a	1.182149	1.182149	25.633	12878	504.45
Mid	3085.562	43.0894	n/a	1.535602	1.535602	15.515	12442	525.70
High	3155.530	20.6369	2.354779	1.580337	3.935182	3.5128	11160	545.41

From our first PT6 testing we were able to gather much of our desired data. We were hoping that the full scale engine would not pose the same problems as the Olympus HP engine in regards to NO_x detection. It was believed that the full-scale PT6 engine might provide enough combustion efficiency improvement over the Olympus HP pilot-scale engine to reduce the THC concentration to a low enough level to obtain NO data, but this was not the case, except for at

High throttle setting. For the second testing trip to Salina we used the second stage carbon filter to be able to accurately gather NO emission concentrations. Our second testing trip data can be seen below in Table 11. As you can see there are two sets of data, one for emissions collection with the carbon filter attached (CF) and one without the carbon filter attached (NCF).

Table 11. Jet A results from the second round of testing

Salina2 Jet A NCF 7/10/2012							
Throttle	**Fuel Specific CO2**	**Fuel Specific CO**	**Corrected Fuel Specific NO**	**Corrected Fuel Specific NO2**	**Corrected Fuel Specific NOx**	**Fuel Specific HC**	**Fuel Specific O2**
	g/kg fuel	**g/kg fuel**	**g/kg fuel**	**g/kg fuel**	**g/kg fuel**	**g/kg fuel**	**g/kg fuel**
Idle	3020.759	59.82033	n/a	0.5280497	0.5280497	25.02221	11232.59
Mid	3119.462	33.26361	1.1663757	0.3776188	1.5439227	6.691896	10793.7
High	3160.79	17.20518	3.4694751	0.7421878	4.2117348	1.249604	10371.44
Salina2 Jet A CF 7/10/2012							
Throttle	**Fuel Specific CO2**	**Fuel Specific CO**	**Corrected Fuel Specific NO**	**Corrected Fuel Specific NO2**	**Corrected Fuel Specific NOx**	**Fuel Specific HC**	**Fuel Specific O2**
	g/kg fuel	**g/kg fuel**	**g/kg fuel**	**g/kg fuel**	**g/kg fuel**	**g/kg fuel**	**g/kg fuel**
Idle	3022.466	62.30586	0.8461784	n/a	0.8461784	23.19537	11147.09
Mid	3116.313	36.00521	2.2051618	n/a	2.2051618	6.304112	10743.79
High	3157.787	19.46799	3.1916851	n/a	3.1916851	0.963799	10229.21

Table 11 shows that we were able to collect information on emission concentrations of both NO and NO_2 during the second round of testing at Salina. The CO_2 data shows that the two runs were very comparable in fuel use and the other pollutant concentrations matched up well with their counterpart in the other test. This shows good reproducibility from test-to-test, at least

for the same day. The remaining Jet A results from our third and fourth testing trips can be seen below in Table 12 and Table 13, respectively.

Table 12. Jet A results from the third round of testing

Salina3 Jet A NCF 9/12/2012								
Throttle	**Fuel Specific CO2**	**Fuel Specific CO**	**Corrected Fuel Specific NO**	**Corrected Fuel Specific NO2**	**Corrected Fuel Specific NOx**	**Fuel Specific HC**	**Fuel Specific O2**	**EGT**
	g/kg fuel	**g/kg fuel**	**g/kg fuel**	**g/kg fuel**	**g/kg fuel**	**g/kg fuel**	**g/kg fuel**	**deg C**
Idle	3026.12	61.8055	n/a	0.447127	0.447127	24.8872	14358.2	483.99
Mid	3119.49	36.3759	1.076745	0.430011	1.506740	7.03011	12872.4	514.50
High	3271.39	48.9040	1.074478	2.191887	3.266338	4.01953	74376.4	202.83
Salina3 Jet A CF 9/12/2012								
Throttle	**Fuel Specific CO2**	**Fuel Specific CO**	**Corrected Fuel Specific NO**	**Corrected Fuel Specific NO2**	**Corrected Fuel Specific NOx**	**Fuel Specific HC**	**Fuel Specific O2**	**EGT**
	g/kg fuel	**g/kg fuel**	**g/kg fuel**	**g/kg fuel**	**g/kg fuel**	**g/kg fuel**	**g/kg fuel**	**deg C**
Idle	3018.81	63.8723	1.045453	0.355364	1.400801	23.8709	11427.5	521.58
Mid	3117.80	37.3593	2.272856	0.352756	2.625685	5.67053	11212.2	447.55
High	3161.03	22.9047	3.625729	0.506215	4.131944	1.05412	13446.5	480.69

For all tests performed, Jet A was the first fuel tested and every attempt was made to follow the same procedures and routines to reproduce our data in the most accurate way possible. Emission concentrations for the “No Carbon Filter” test during the third testing trip on 9/12/2012 were not used for calculating average emissions for Jet A because it was noticed that the sampling probe moved off-center of the exhaust plume during sampling, causing the data collected to be skewed.

Table 13. Jet A results from the fourth round of testing

Salina4 Jet A NCF 10/24/2012							
Throttle	Fuel Specific CO2	Fuel Specific CO	Corrected Fuel Specific NO	Corrected Fuel Specific NO2	Corrected Fuel Specific NOx	Fuel Specific HC	EGT
	g/kg fuel	g/kg fuel	g/kg fuel	g/kg fuel	g/kg fuel	g/kg fuel	deg C
Idle	3026.997	68.95155	n/a	0.4814972	0.4814972	19.22721	549.8649
Mid	3110.572	38.81837	0.649182	0.4498287	1.0989779	7.095689	553.6509
High	3188.213	25.30423	2.760133	0.9784641	3.7385856	2.501891	320.7347
Salina4 Jet A CF 10/24/2012							
Throttle	Fuel Specific CO2	Fuel Specific CO	Corrected Fuel Specific NO	Corrected Fuel Specific NO2	Corrected Fuel Specific NOx	Fuel Specific HC	EGT
	g/kg fuel	g/kg fuel	g/kg fuel	g/kg fuel	g/kg fuel	g/kg fuel	deg C
Idle	3016.832	69.74143	1.243724	0.1220994	1.3658564	21.67819	273.1384
Mid	3107.813	39.90981	2.153602	0.157674	2.3112265	7.358891	517.8491
High	3176.267	23.85365	3.408287	0.3546906	3.763	1.490535	448.6971

The average emission concentrations from the viable data collected on Jet A fuel can be seen below in Table 14. These results follow the trends we were expecting to find based on earlier results. Exhaust gas temperature (EGT) is the only pollutant that does not follow the trends we would expect to see and the trends reported in the literature as can be seen below in Figure 11. EGT should increase as throttle increases due to the higher pressure and more fuel being burned in the combustion chamber [32]. In the average fuel tables, NO_x is titled "Estimated NO_x" to reiterate that NO and NO_2 were not collected simultaneously, but are taken from different runs of the same fuel. Table 14 will be the data set used when comparing

alternative fuel emission concentrations to determine if they produce increased or decreased pollutant concentrations.

Table 14. Average Jet A PT6 Results

Salina Jet A Average Emissions								
Throttle	**Fuel Specific CO2**	**Fuel Specific CO**	**Corrected Fuel Specific NO**	**Corrected Fuel Specific NO2**	**Corrected Fuel Specific Estimated NOx**	**Fuel Specific HC**	**Fuel Specific O2**	**EGT**
	g/kg fuel	g/kg fuel	g/kg fuel	g/kg fuel	g/kg fuel	g/kg fuel	g/kg fuel	deg C
Idle	3020.7	64.7606	1.045118	0.504773	1.5498918	22.8108	11308.7	466.543
Mid	3114.9	37.1192	2.210540	0.413723	2.6242638	6.46527	10990.4	491.651
High	3167.5	21.9400	3.408567	0.860326	4.2688931	1.38568	11873.4	432.705

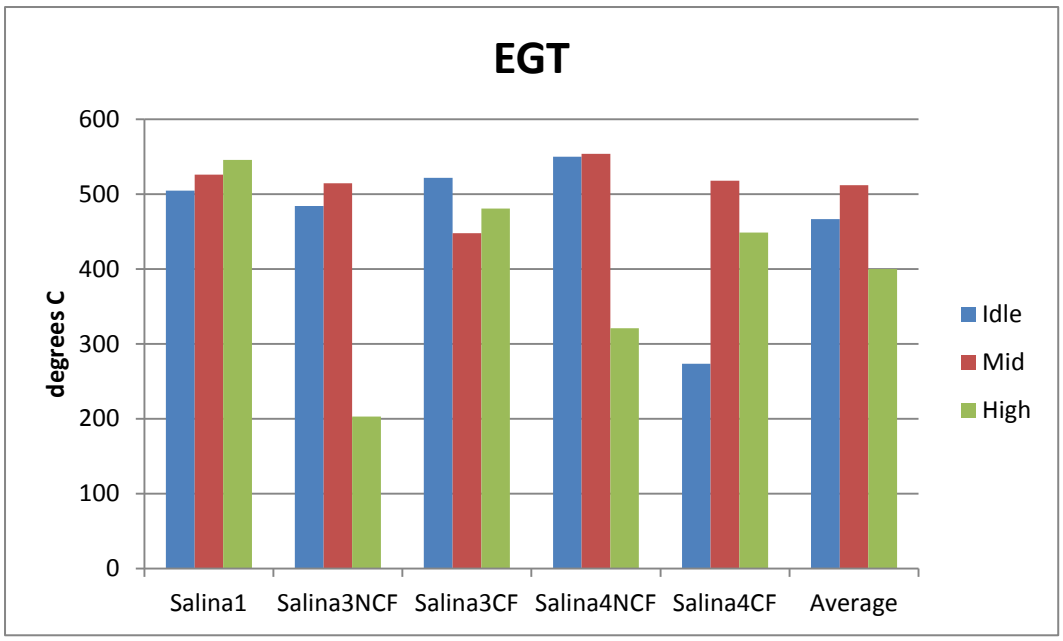

Figure 11. Full-Scale Jet A EGT Results

3.2.2 HRJ (Hydroprocessed Renewable Jet) Fuel

The HRJ alternative fuel was tested during the third and fourth trips to Salina. To obtain more accurate fuel-specific emissions data for the HRJ data, H:C ratio and specific gravity of the fuel were all obtained. This information was gathered from other published research papers because this data could not be collected in-house. Average values for specific gravity and H:C ratio of 0.779 and 2.05:,1 respectively, when blended 50/50 by volume with Jet A, were taken from the literature and used in the post processor calculations of the Semtech-DS [41, 35]. These results can be seen below. Table 15 shows the third trip results, Table 16 shows the fourth trip results, and Table 17 shows the average HRJ results.

Table 15. HRJ results from the third round of testing

Salina3 HRJ NCF 9/12/2012								
Throttle	Fuel Specific CO2	Fuel Specific CO	Corrected Fuel Specific NO	Corrected Fuel Specific NO2	Corrected Fuel Specific NOx	Fuel Specific HC	Fuel Specific O2	EGT
	g/kg fuel	g/kg fuel	g/kg fuel	g/kg fuel	g/kg fuel	g/kg fuel	g/kg fuel	deg C
Idle	2992.38	65.6679	n/a	1.209237	1.209237	22.1965	11421.7	517.60
Mid	3086.65	39.1706	0.325812	1.313519	1.639331	5.22117	11087.7	445.89
High	3134.12	31.9777	2.955845	1.753486	4.709303	0.78194	19550.6	438.70
Salina3 HRJ CF 9/12/2012								
Throttle	Fuel Specific CO2	Fuel Specific CO	Corrected Fuel Specific NO	Corrected Fuel Specific NO2	Corrected Fuel Specific NOx	Fuel Specific HC	Fuel Specific O2	EGT
	g/kg fuel	g/kg fuel	g/kg fuel	g/kg fuel	g/kg fuel	g/kg fuel	g/kg fuel	deg C
Idle	2990.75	66.3465	0.653132	0.453254	1.106375	22.3114	11380.5	531.65
Mid	3079.57	42.0884	1.917663	0.466491	2.384116	5.98235	11055.5	498.98
High	3131.01	33.0689	3.528	0.8306796	4.3587459	0.717694	18810.76	436.538

As seen in Table 15 and table 16, there was some variation between the third trip data and the fourth trip data regarding the HC emissions. As seen in the literature, hydrocarbon emissions displayed the most variation of all pollutant emissions, due to the effect of temperature and humidity on their formation and the vast number of compounds they encompass [31]. Another more variable pollutant emission, at least from the data we collected, was NO_2. Oxides of nitrogen are largely dependent on the temperature of the combustion flame inside the gas turbine engine and could be altered by the composition of the alternative fuel, the ambient temperature, or the ambient humidity.

Table 16. HRJ results from the fourth round of testing

Salina4 HRJ NCF 10/24/2012							
Throttle	**Fuel Specific CO2**	**Fuel Specific CO**	**Corrected Fuel Specific NO**	**Corrected Fuel Specific NO2**	**Corrected Fuel Specific NOx**	**Fuel Specific HC**	**EGT**
	g/kg fuel	**g/kg fuel**	**g/kg fuel**	**g/kg fuel**	**g/kg fuel**	**g/kg fuel**	**deg C**
Idle	2964.754	74.95548	n/a	0.701011	0.701011	26.99283	488.323
Mid	3071.911	43.07983	0.1261547	0.8633646	0.9894254	7.931625	558.709
High	3134.454	25.5078	3.0255967	1.1137238	4.1393149	0.995179	416.393
Salina4 HRJ CF 10/24/2012							
Throttle	**Fuel Specific CO2**	**Fuel Specific CO**	**Corrected Fuel Specific NO**	**Corrected Fuel Specific NO2**	**Corrected Fuel Specific NOx**	**Fuel Specific HC**	**EGT**
	g/kg fuel	**g/kg fuel**	**g/kg fuel**	**g/kg fuel**	**g/kg fuel**	**g/kg fuel**	**deg C**
Idle	2961.674	73.9784	0.8031989	0.2277735	1.0309558	27.93567	548.073
Mid	3070.773	43.5813	1.7018729	0.2919392	1.9938508	8.162004	422.742
High	3132.883	28.18177	3.1337017	0.5614751	3.6951602	1.172904	441.162

Table 17. Average HRJ Results

Average HRJ Results								
Throttle	Fuel Specific CO2	Fuel Specific CO	Corrected Fuel Specific NO	Corrected Fuel Specific NO2	Corrected Fuel Specific Estimated NOx	Fuel Specific HC	Fuel Specific O2	EGT
	g/kg fuel	g/kg fuel	g/kg fuel	g/kg fuel	g/kg fuel	g/kg fuel	g/kg fuel	deg C
Idle	2977.3	70.2370	0.728165	0.95512	1.68329	24.8591	11401.1	521.414
Mid	3077.2	41.9800	1.809768	1.08844	2.89820	6.82429	11071.6	481.582
High	3133.1	29.6840	3.330850	1.43360	4.76445	0.91693	19180.6	433.199

3.2.3 FT (Fischer-Tropsch) Fuel

The Fischer-Tropsch fuel testing was conducted at the same time as the HRJ fuel testing, during the third and fourth testing trips. Also, the FT fuel specific gravity and H:C ratio values, 0.781 and 2.05:1 respectively when blended 50/50 by volume with Jet A, for post processing analysis were averages of the data available in the literature [41, 42]. The fuel specific emission results for the FT blends can be seen below in Table 18 for the third trip and Table 19 for the fourth trip with averages shown in Table 20.

Table 18. FT results from the third round of testing

Salina3 FT NCF 9/12/2012								
Throttle	**Fuel Specific CO2**	**Fuel Specific CO**	**Corrected Fuel Specific NO**	**Corrected Fuel Specific NO2**	**Corrected Fuel Specific NOx**	**Fuel Specific HC**	**Fuel Specific O2**	**EGT**
	g/kg fuel	**g/kg fuel**	**g/kg fuel**	**g/kg fuel**	**g/kg fuel**	**g/kg fuel**	**g/kg fuel**	**deg C**
Idle	2997.87	66.4904	n/a	1.345364	1.345364	19.9417	11325.0	539.824
Mid	3078.70	43.6293	n/a	1.467768	1.467768	5.57817	11157.7	444.588
High	3130.40	37.9998	2.639690	1.645425	4.285088	0.51508	21383.4	438.349
Salina3 FT CF 9/12/2012								
Throttle	**Fuel Specific CO2**	**Fuel Specific CO**	**Corrected Fuel Specific NO**	**Corrected Fuel Specific NO2**	**Corrected Fuel Specific NOx**	**Fuel Specific HC**	**Fuel Specific O2**	**EGT**
	g/kg fuel	**g/kg fuel**	**g/kg fuel**	**g/kg fuel**	**g/kg fuel**	**g/kg fuel**	**g/kg fuel**	**deg C**
Idle	3005.01	66.5097	0.503027	0.251806	0.754850	18.2980	11999.2	529.511
Mid	3079.63	43.9685	1.697276	0.264093	1.961370	4.94165	10881.3	546.306
High	3138.39	57.4193	3.097414	0.824679	3.922099	0.57039	35985.5	333.939

Table 19. FT results from the fourth round of testing

Salina4 FT NCF 10/24/2012							
Throttle	Fuel Specific CO2	Fuel Specific CO	Corrected Fuel Specific NO	Corrected Fuel Specific NO2	Corrected Fuel Specific NOx	Fuel Specific HC	EGT
	g/kg fuel	g/kg fuel	g/kg fuel	g/kg fuel	g/kg fuel	g/kg fuel	deg C
Idle	2963.695	73.15003	n/a	1.356895	1.356895	27.73941	557.7058
Mid	3071.966	45.01327	n/a	1.5622762	1.5622762	7.206032	451.2793
High	3132.201	32.2302	2.7711215	1.6516906	4.4228066	0.729019	414.9748
Salina4 FT CF 10/24/2012							
Throttle	Fuel Specific CO2	Fuel Specific CO	Corrected Fuel Specific NO	Corrected Fuel Specific NO2	Corrected Fuel Specific NOx	Fuel Specific HC	EGT
	g/kg fuel	g/kg fuel	g/kg fuel	g/kg fuel	g/kg fuel	g/kg fuel	deg C
Idle	2963.018	73.89082	0.4694088	0.375663	0.8450994	27.64854	553.8277
Mid	3076.541	43.71699	1.3101215	0.3643315	1.6744199	6.327722	331.4692
High	3134.556	34.65411	2.7821271	0.7934144	3.5755525	0.679697	401.2259

Table 20. Average FT Results

Average FT Results								
Throttle	Fuel Specific CO2	Fuel Specific CO	Corrected Fuel Specific NO	Corrected Fuel Specific NO2	Corrected Fuel Specific Estimated NOx	Fuel Specific HC	Fuel Specific O2	EGT
	g/kg fuel	g/kg fuel	g/kg fuel	g/kg fuel	g/kg fuel	g/kg fuel	g/kg fuel	deg C
Idle	2982.39	70.0102	0.486218	1.351129	1.837348	23.4069	11662.1	545.217
Mid	3076.71	44.0820	1.503698	1.515022	3.018721	6.01339	11019.5	443.411
High	3133.88	40.5758	2.939770	1.648558	4.588328	0.62354	28684.5	397.122

From Table 18 and Table 19 it can be seen that, similar to the HRJ fuel, hydrocarbon emissions showed the largest variation of the pollutants between tests, along with NO_2. As before, this is not surprising due to their sensitivity to so many formation parameters. Another pollutant that showed some variation from test to test was EGT. However, it is possible that our thermocouple used to collect EGT data was not functioning properly for the entirety of the third and fourth testing trips. This conclusion came from the fact that we saw some negative exhaust temperature values towards the latter stage of sampling. We know that it was not possible for this to be actually occurring. It would have been highly obvious if temperatures dropped from 500°C to less than 0°C in a matter of seconds. We believe that the extended testing in high temperatures, the duration of testing, and the high velocity of the exhaust gas caused the thermocouple to lose connection during sampling rendering most of the EGT information from the third and fourth testing trips of no value, or at least highly questionable.

3.2.4 Alternative Fuel Results Compared to Jet A

The two tables below show how the emission concentrations of the alternative fuel blends compare to the emission concentrations of conventional Jet A. Comparison between the alternatives and conventional Jet A are shown normalized to Jet A emissions (that is, the alternative fuel concentration divided by the corresponding Jet A concentration). Therefore a value less than 1.0 represents a reduction relative to Jet A and a value larger than 1.0 represents an increase relative to the corresponding Jet A result. Table 21 shows HRJ data normalized to Jet A and Table 22 shows FT data normalized to Jet A. Figures 12-26 show the average pollutant concentrations for each fuel type, these figures use units of g/kg fuel instead of normalizing to Jet A to show how the concentrations varied with throttle setting.

Table 21. Average HRJ data normalized to average Jet A data

HRJ / Jet A Comparison								
Throttle	**Fuel Specific CO2**	**Fuel Specific CO**	**Corrected Fuel Specific NO**	**Corrected Fuel Specific NO2**	**Corrected Fuel Specific Estimated NOx**	**Fuel Specific HC**	**Fuel Specific O2**	**EGT**
	g/kg fuel	**g/kg fuel**	**g/kg fuel**	**g/kg fuel**	**g/kg fuel**	**g/kg fuel**	**g/kg fuel**	**deg C**
Idle	0.9853	1.05243	0.636181	1.93684	1.0278229	1.14424	1.008177	1.117612
Mid	0.9885	1.10380	0.817704	2.520847	1.0957292	1.01029	1.007394	0.97952
High	0.9868	1.27239	0.947069	1.559291	1.0739456	0.52984	1.615433	1.001144
Avg.	0.9869	1.14287	0.800318	2.005659	1.0658326	0.89479	1.210334	1.032759

Table 22. Average FT data normalized to average Jet A data

FT / Jet A Comparison								
Throttle	**Fuel Specific CO2**	**Fuel Specific CO**	**Corrected Fuel Specific NO**	**Corrected Fuel Specific NO2**	**Corrected Fuel Specific Estimated NOx**	**Fuel Specific HC**	**Fuel Specific O2**	**EGT**
	g/kg fuel	**g/kg fuel**	**g/kg fuel**	**g/kg fuel**	**g/kg fuel**	**g/kg fuel**	**g/kg fuel**	**deg C**
Idle	0.98701	1.04903	0.424797	2.739876	1.1218913	1.07740	1.031252	1.168632
Mid	0.98840	1.15907	0.679414	3.508813	1.141291	0.89025	1.002654	0.901882
High	0.98705	1.73926	0.835872	1.79309	1.0342451	0.36031	2.415864	0.917767
Avg.	0.98749	1.31579	0.646694	2.680593	1.0991425	0.77598	1.483257	0.996094

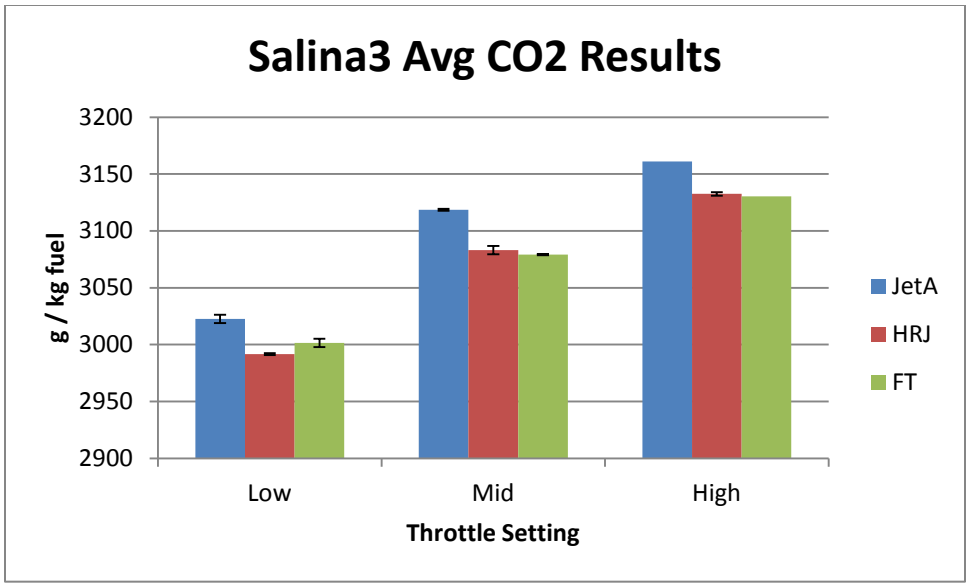

Figure 12. Salina3 Average CO2 Results

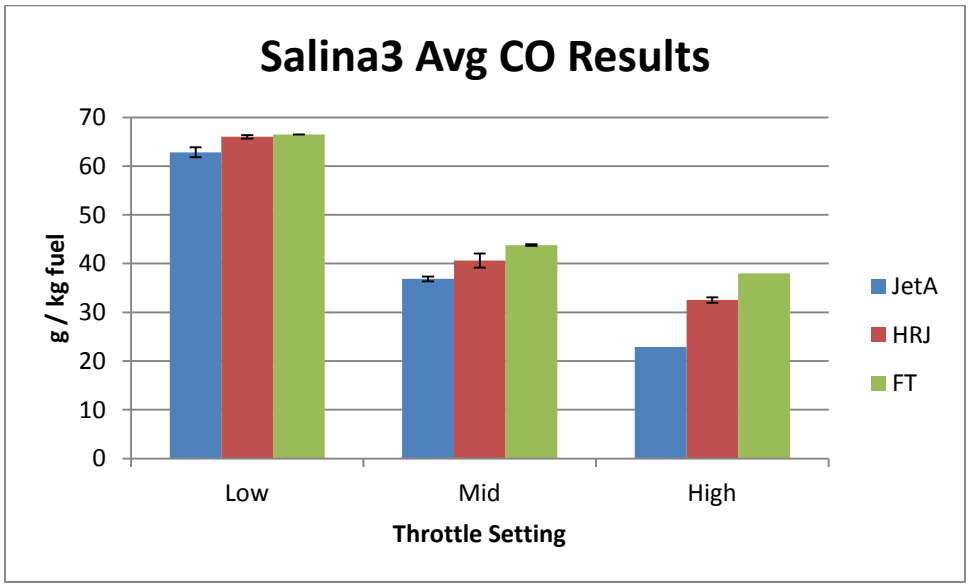

Figure 13. Salina3 Average CO Results

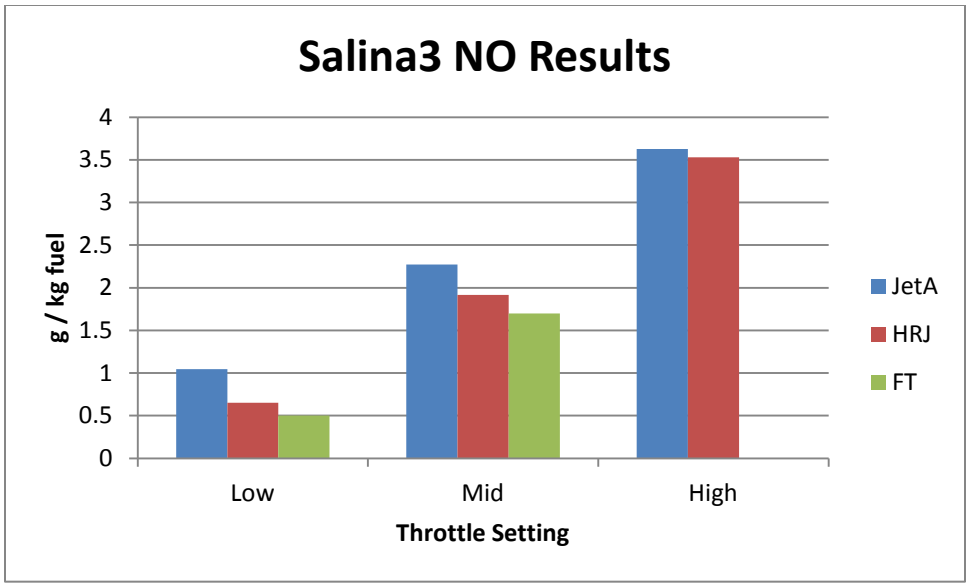

Figure 14. Salina3 Average NO Results

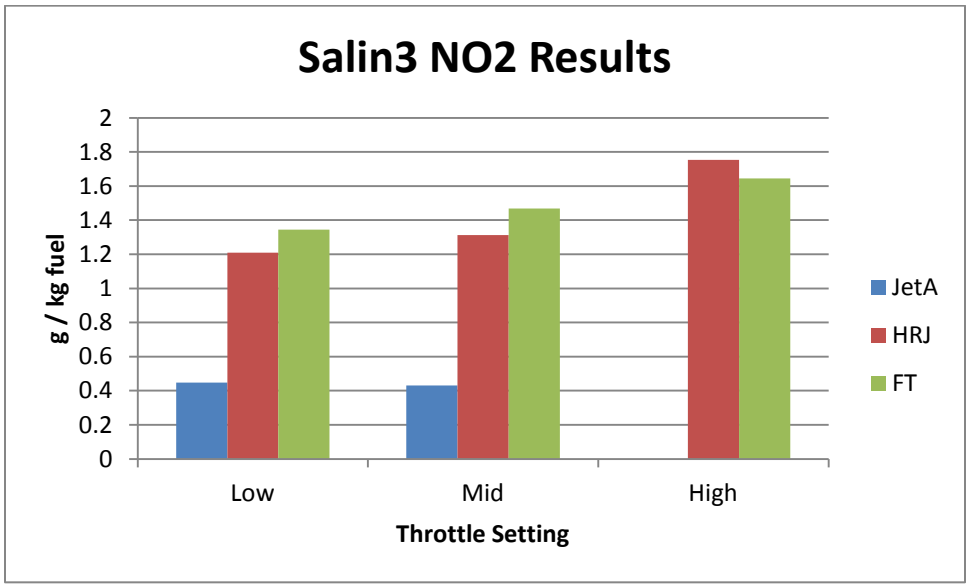

Figure 15. Salina3 Average NO2 Results

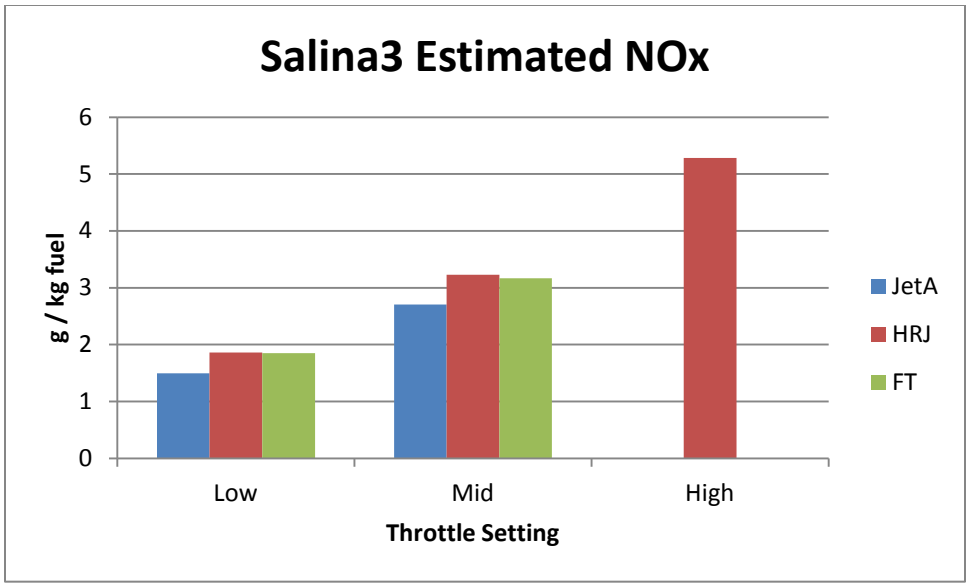

Figure 16. Salina3 Estimated NOx Results

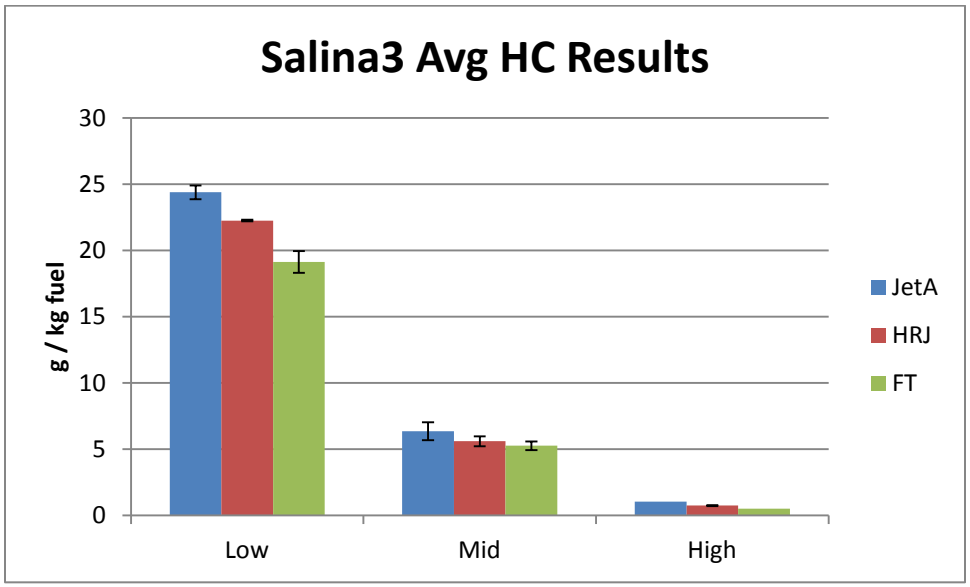

Figure 17. Salina3 Average HC Results

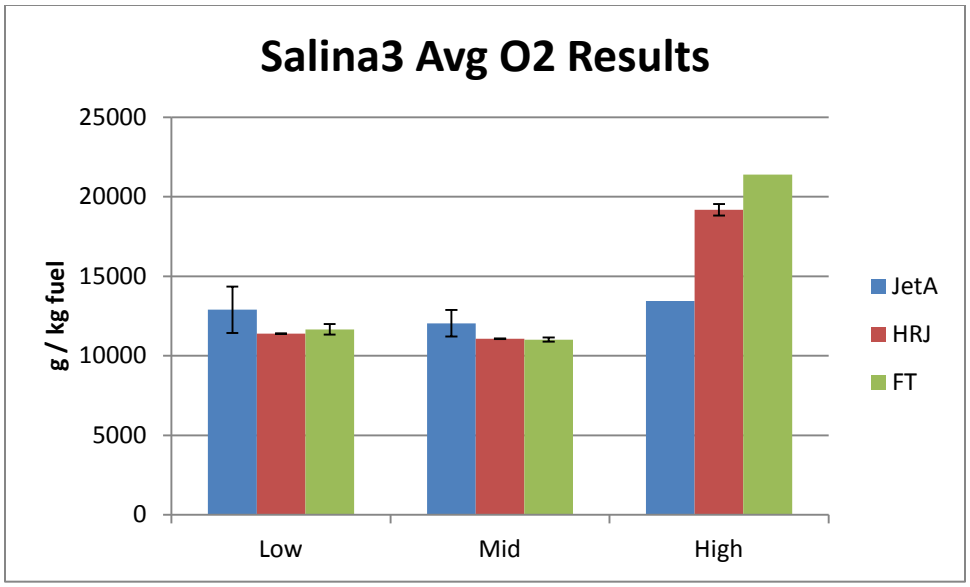

Figure 18. Salina3 Average O2 Results

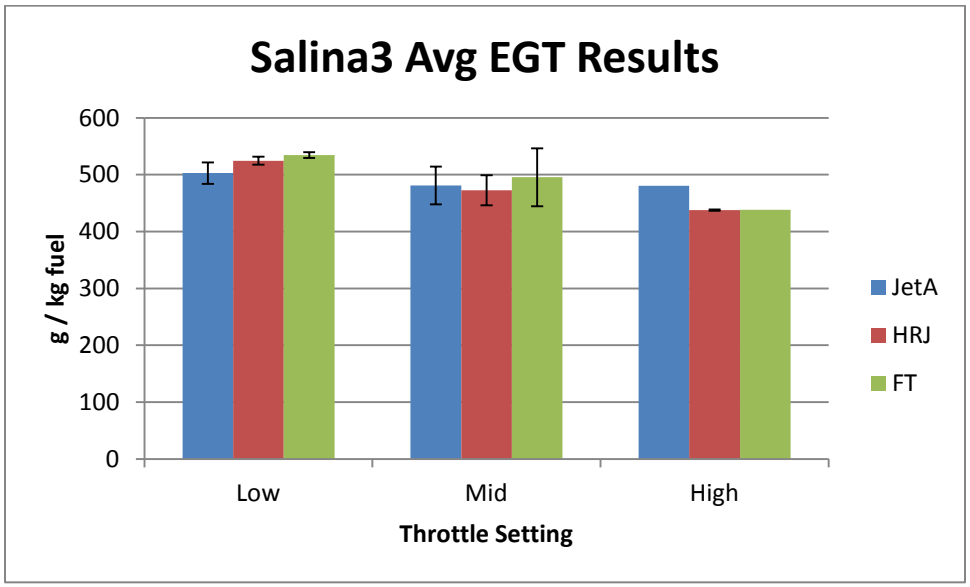

Figure 19. Salina3 Average EGT Results

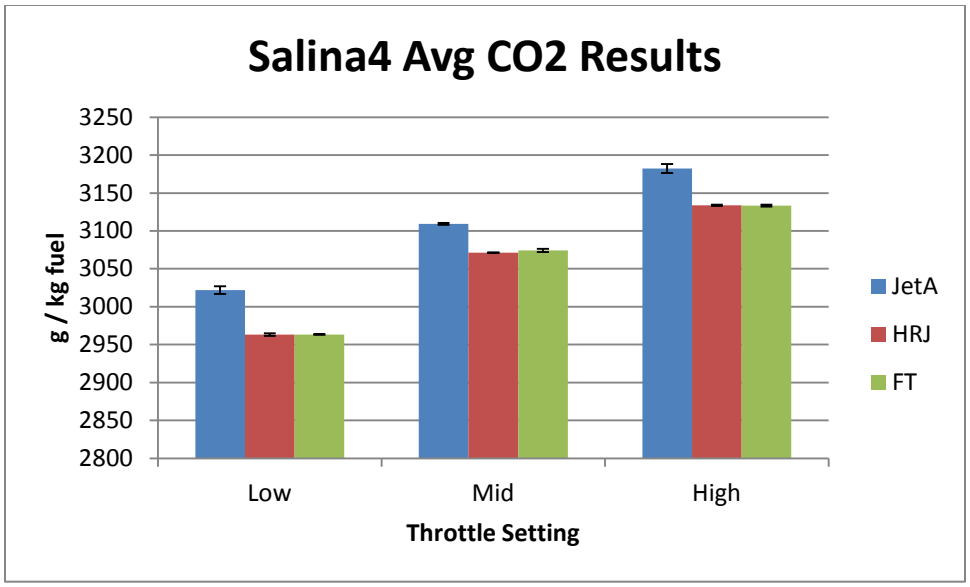

Figure 20. Salina4 Average CO2 Results

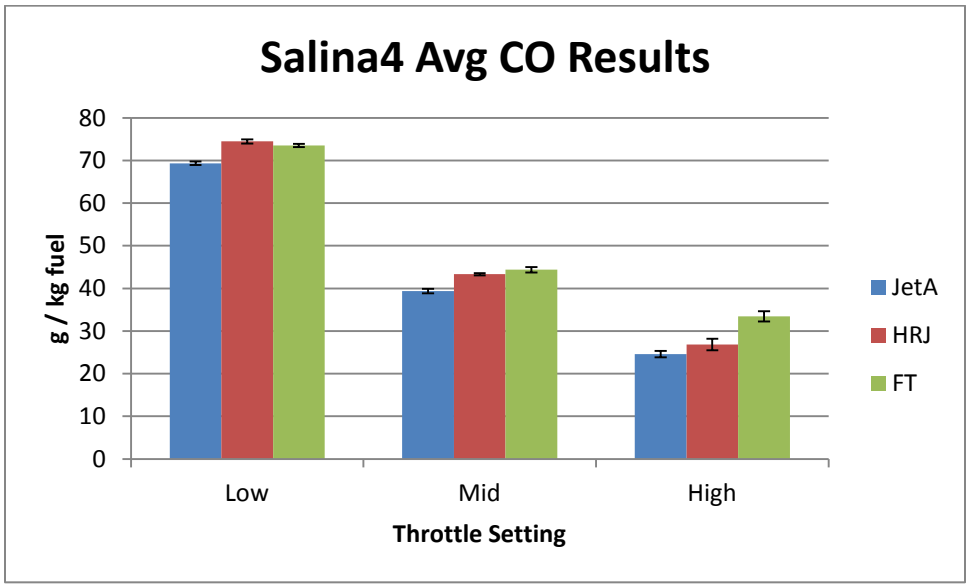

Figure 21. Salina4 Average CO Results

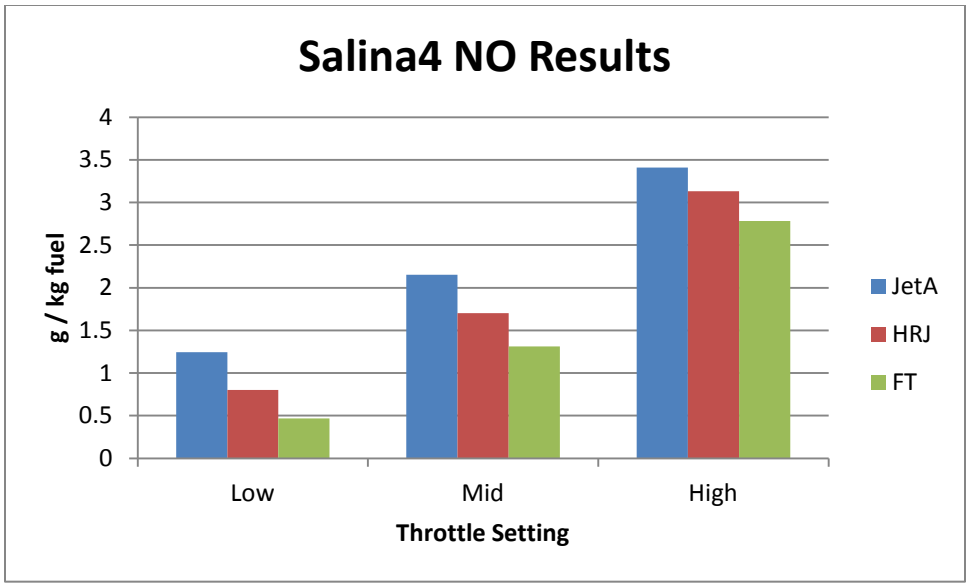

Figure 22. Salina4 NO Results

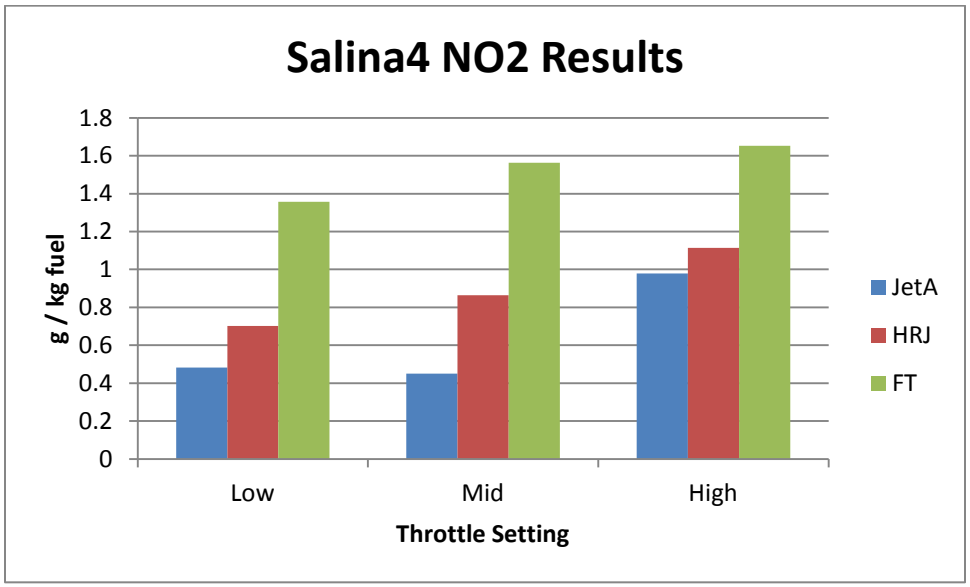

Figure 23. Salina4 NO2 Results

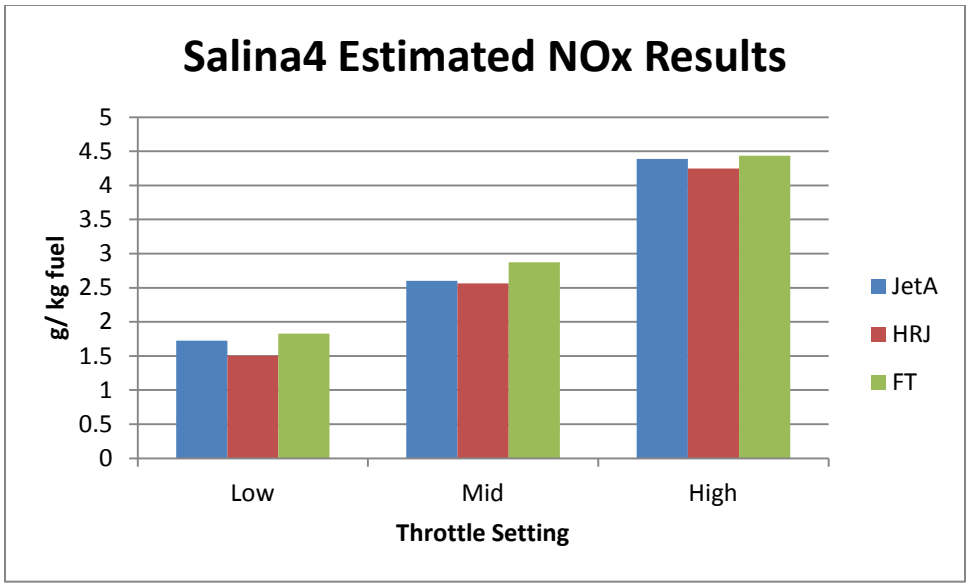

Figure 24. Salina4 Estimated NOx Results

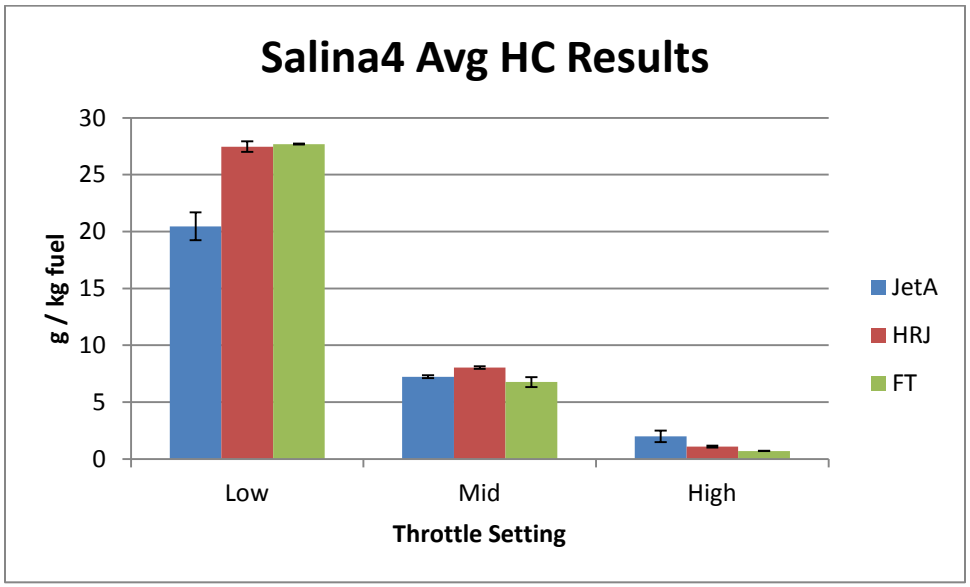

Figure 25. Salina4 Average HC Results

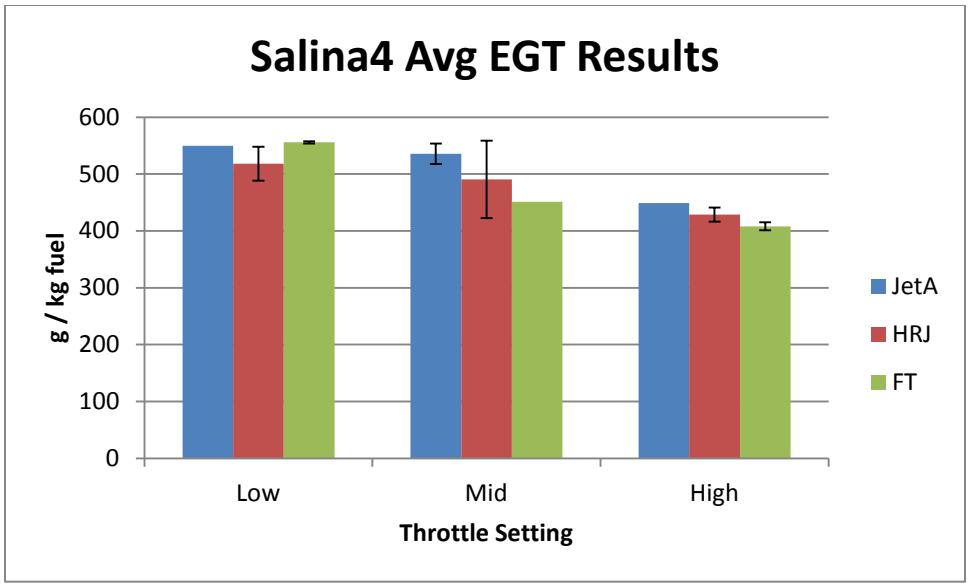

Figure 26. Salina4 Average EGT Results

3.3 Discussion of Results

3.3.1Olympus HP

After the successful completion of a couple test runs and sample collections, we sent our data to Sensors-Inc to see if they had an explanation for the issues we were encountering. After they examined our data, the solution was to employ a secondary carbon scrubber. The use of the scrubber solved our sampling issue but there seemed to be some confusion among the three technicians we spoke with about the cause of the problem. The trouble seems to stem from the Semtech-DS use of a NDUV analyzer for NO_x analysis. This NDUV analyzer uses optical lens to gather information on the composition and concentration of the gas stream it is analyzing. If there is a large concentration of heavy hydrocarbons present in the gas stream the analyzer can have difficulties "seeing" the oxides of nitrogen present due to their small size relative to the hydrocarbons. This non-dispersive analyzer uses an algorithm to decode the information gathered from the optics and report a pollutant concentration [36]. This analyzer has a lower limit sensitivity of 10ppm for nitric oxide [38]. As can be seen from the data collected, our NO

emissions fell well below the 10ppm limit. Therefore, our sampling difficulties were caused by a combination of increased heavy hydrocarbons and a small concentration of NO present in the exhaust gas. The second stage carbon filter scrubber allows the NDUV analyzer to "see" the NO compounds by scrubbing all other pollutants out of the gas stream and only allowing NO to pass through.

The results presented in Table 9 are the most accurate collected emissions data from the Olympus HP testing runs. Throttle increases from Idle to High cause the percentage of CO_2 in the exhaust gas to increase. This is due to the fact that CO2 emissions are a product of complete combustion and are directly related to the amount of fuel consumed. As the throttle increases and more fuel is being burned in the combustion chamber of the engine, the percentage of carbon dioxide in the exhaust also increases. Carbon monoxide (CO) and hydrocarbons (HC) emissions should follow the inverse of CO_2 emissions [14]. As throttle increases, more air and fuel is being combusted at higher temperatures and higher pressures. This leads to higher combustion efficiency and a more complete combustion. CO and HC emissions are products of incomplete combustion, thus their emissions should decrease with an increase of throttle. This was the observed trend from Idle to Mid throttle setting, but not from Mid to High throttle setting. During actual use of an aircraft there would be a substantial load on the engine (cargo, fuel, passengers, etc.) that would cause an increase in the amount of work needed to be done by the engine when increasing throttle settings and therefore an increase in combustion efficiency. Our testing procedure was for a test stand application and did not allow the addition of load on the engine. Therefore, when the throttle increased from the Mid throttle to High throttle setting the fuel was not actually being completely combusted but more of being funneled into the exhaust gas stream of the engine, causing an increase in CO and HC emissions.

3.3.2 PT6 Results

Comparing the alternative fuel emission results to the conventional Jet A fuel emission results, there were some noticeable trends to document. For both of the alternative fuels, HRJ and FT, the CO_2 emissions were relatively the same as the Jet A. For both testing dates and for all throttle settings, the alternative fuels showed 98 – 99% CO_2 emissions relative to the average Jet A emissions. As previously mentioned, CO_2 emissions are directly related to fuel consumed and throttle setting. The fact that all the alternative fuel testing closely resembles the Jet A testing results expresses that all our throttle settings from run-to-run were similar and that procedure repeatability was not an issue. Even though the g/ kg fuel consumed data might show a reduction in CO_2 emissions further investigation needs to be done before it can be said that the alternative fuels reduce total CO_2 emissions. The alternative fuels have a higher H:C ratio and also may have a significant oxygen content relative conventional jet fuel, therefore less carbon per fuel molecule and less energy [43]. This leads to more fuel needing to be consumed to reach the same throttle level and offsetting any reduction in CO_2 emissions. Figures 27 & 28 show the fuel flow results for the third and fourth testing trips, in gallons per hour, and turbine inner temperature (TIT), in degrees Celsius, for the three fuels tested.

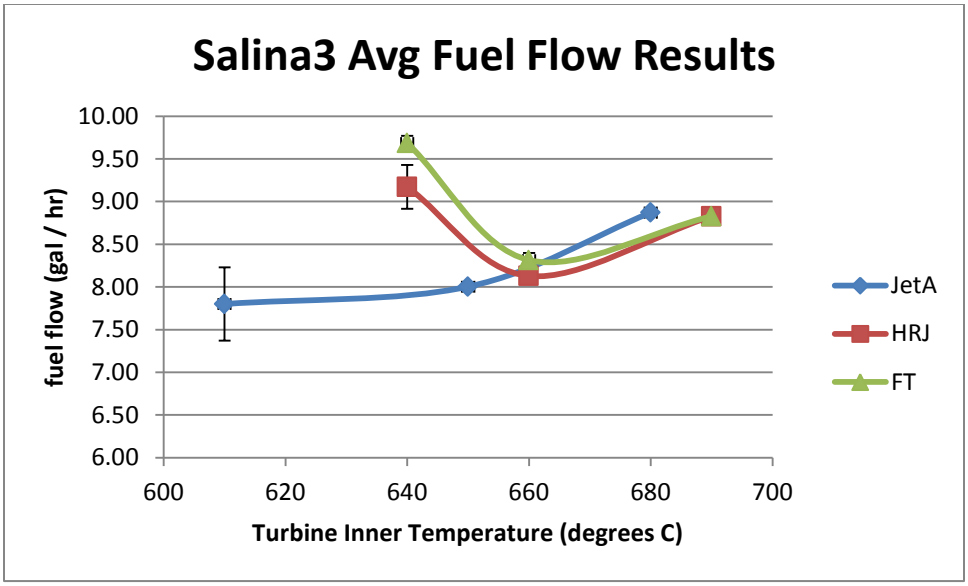

Figure 27. Salina3 Average Fuel Flow Results

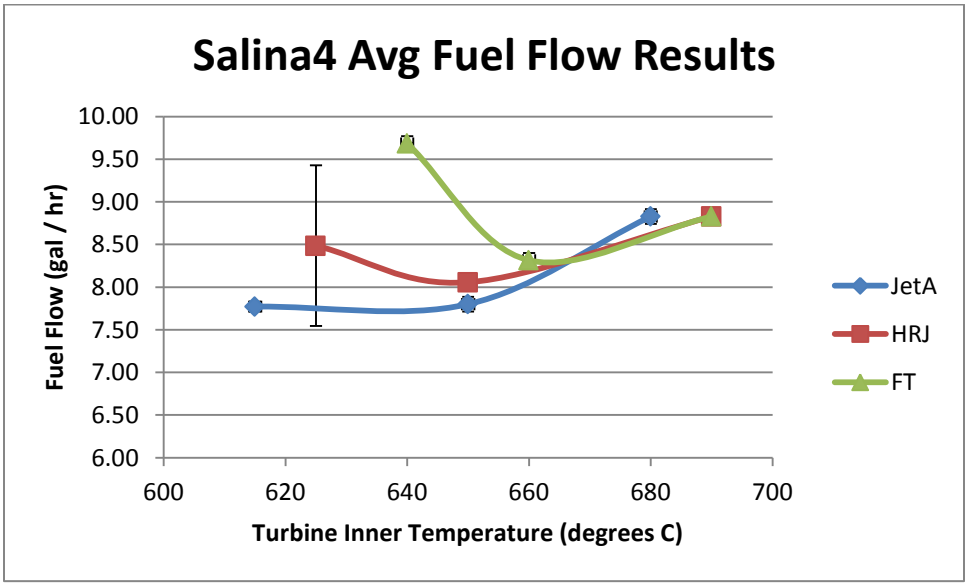

Figure 28. Salina4 Average Fuel Flow Results

The TIT reflects the throttle setting, with higher throttle settings producing a higher TIT. As seen in Figures 27 & 28 the HRJ and FT fuels both produce higher TIT versus Jet A but require a higher fuel flow (more fuel) to do so. Overall for the short durations of our testing, it does not appear that our testing is using a drastically larger amount of fuel, thus a significant change in CO_2 emissions does not appear to be occurring. Our test runs were only using 10-15

gallons per test, so it would be difficult to quantify any difference in fuel use between tests. It is expected due to the similar energy content of alternative fuels relative to conventional aviation fuels that CO_2 emissions from actual combustion of the alternative fuels should be analogous to petrojet. Alternative fuels have the potential to reduce total well-to-wake CO_2 emissions because of the CO_2 used by their respective feedstock during the growing season. To truly identify if these alternative fuels are reducing their total CO_2 emissions a life cycle analysis (LCA) should be done because it takes into account the production, transportation, and use of each fuel.

Carbon dioxide is not an important outdoor air pollutant in the common sense because it does not chemically react further to form other pollutants nor is it harmful to human health at typical mixing ratios [44]. It does play a subtle role in stratospheric ozone depletion because global warming near the Earth's surface due to carbon dioxide enhances global cooling of the stratosphere and such cooling feeds back to the ozone layer.

Carbon monoxide emissions from the alternative fuels were not as consistent as the CO_2 results but did follow a general pattern. For both the HRJ and FT fuels, CO emissions were higher than Jet A emissions for all throttle settings and both testing dates with larger increases over Jet A seen at higher throttle settings. Both displayed about a 5% increase at Idle, and a roughly 10% increase at Mid throttle, with a dramatic increase at the High throttle setting. Also, at this High throttle setting there was significant variation between testing dates, making the actual High throttle emission values difficult to pin-point in our limited data sets. It has been demonstrated that CO emissions are significantly dependent on fuel aromatic content, with heavier aromatics having more of an effect [45]. Increasing aromatic content or molecular weight of the fuel reduces combustion efficiency and therefore increases CO. Another possibility is that the alternative fuels had an effect on the spray pattern of the fuel. CO forms in fuel rich, or

oxygen deficient, zones in the combustion chamber. A change in the fuel spray pattern could alter emission concentrations.

Carbon monoxide is listed as a criteria pollutant by the EPA and as such has to meet National Ambient Air Quality Standards (NAAQS) [30]. CO plays a small role in ozone formation in urban areas, but plays a larger role in ozone formation in the background troposphere [44]. It is not as important with respect to stratospheric ozone reduction or acid deposition. It is however, an important component of urban and indoor air pollution because of its harmful short-term effects. Carbon monoxide poisoning occurs when it dissolves in blood and replaces oxygen as an attachment to hemoglobin and causes suffocation. It can also interfere with oxygen diffusion in cellular mitochondria and within intercellular oxidation. Exposure to 300ppm for an hour will cause headaches while exposure to 700ppm for an hour will result in death.

Hydrocarbon emissions are fuel molecules that survive combustion and are therefore products of incomplete combustion [14]. In this way, they are very similar to CO emissions, with largely the same factors contributing to their formation. That being stated, it is very interesting to see the combination of CO and HC emission results from the alternative fuels because they show different trends from each other. Overall, for both fuels and both testing dates, HC emissions decreased and decreased substantially at High throttle setting where CO showed the largest increases. Emissions of HC at the Idle throttle setting showed the most variation between run-to-run for both fuels, with the average of the two testing dates showing increases over Jet A HC emissions at Idle for both alternative fuels.

CO and HC emissions are both products of incomplete combustion, so it is unusual that these two pollutants would have such differing responses to the combustion of the alternative fuels. There are some possible explanations as to why this is happening though. CO emissions are more of a representative of combustion efficiency than HC emissions due to carbon monoxide's larger energy requirement to convert to CO_2. Therefore, CO emissions are more dependent on flame temperature than HC emission. HRJ and FT combustion did show a slight decline in the exhaust gas temperatures, 1% and 5% respectively, but as mentioned previously there is limited confidence in the accuracy of the EGT data due to thermocouple malfunctions. While HC emissions are still affected by EGT, the degree might be less due to the simpler molecules in the alternative fuels. Conventional petrojet contains a wider spread of hydrocarbons, including more heavy compounds than alternative fuels [18]. The simple hydrocarbons in the HRJ and FT fuel could combust more readily at lower temperatures while CO does not, leading to the trends we see in the data. Thus, a reduction in HC emissions would be due primarily to the chemical composition of the fuel, which allows more complete combustion even at reduced temperatures [43].

Oxides of nitrogen (NO and NO_2) form from dissociation of O_2 and N_2 in the ambient air. Therefore, NO_x emission concentrations are almost entirely due to the temperature of combustion, with an increasing temperature correlating to an increase in NO_x. The alternative fuels NO emission results were consistent from run-to-run for each fuel, with the largest reductions shown at Idle throttle setting. The FT fuel showed a larger reduction in NO compared to the HRJ, but both consistently showed reductions over Jet A concentrations. As throttle increased, NO concentrations approached those of Jet A. NO_2 emissions did not show the same behavior however. From test date to test date, NO_2 displayed large variations. For all tests and all

throttle settings the alternative fuel NO_2 concentrations were larger and NO concentrations smaller than the corresponding Jet A emissions. Previous studies working with biodiesel fuel in internal combustion engines found that differences in the chemical properties and cetane number will influence injection timing and subsequent premixed and diffusion burn characteristics during combustion, all of which affect NO_x production [43].

In internal combustion engines, the most likely major contributors to NO_x increases are advanced injection timing, prompt NO_x formation, and changes in fuel composition that affect fuel spray or ignition patterns of combustion, such as a faster flame front and less ignition delay [46]. Similarly, in a turbine engine, the faster flame front could result in a higher TIT, as seen at low power in Figure 18, which would cause more NO_2. As the flame front progresses, cooler mixing zones quench the NO_2 and keep them from converting back into NO. Information on the alternative fuels' cetane number would have been beneficial for further analysis, but this information was not able to be obtained. Overall for both alternative fuels, NO_2 concentration was double that of Jet A with the FT concentration showing higher concentrations. Therefore, even though both fuels displayed reductions in NO, the total estimated NO_x for both alternative blends showed increases over average Jet A results.

Nitric oxide (NO) is a precursor to tropospheric ozone, nitric acid (HNO_3), and particulate matter (NO_3^-) [44]. NO does not directly affect acid deposition but nitric acid does, nor does NO directly affect global warming but ozone and NO_3^- do. There are no known directly harmful human health effects from typical atmospheric mixing ratios of NO. Nitrogen dioxide is an intermediary between NO emission and ozone formation. It too is a precursor to nitric acid and ozone formation. Although exposure to high mixing ratios of NO_2 harms the lungs and increase respiratory infections, epidemiologic evidence indicates typical mixing ratios have little

effect on the general public. Children and asthmatics are more susceptible to illness associated with high nitrogen dioxide levels. NO_2 may trigger asthma by damaging or irritating and sensitizing the lungs, making people more susceptible to allergic responses to allergens.

Of more concern for nitrogen oxides is airport emissions' influence on the surrounding local air quality. NO_x and hydrocarbon emissions may react in the presence of sunlight to form photochemical smog and ozone, both of which are known to have adverse human health effects and are detrimental to the environment. Another relative air quality pollutant is particulate matter (PM), which was unable to be collected during this project. PM affects visibility and has many negative respiratory correlations associated with them. Standard LTO cycles are intended to represent the emissions from an aircraft that would have a direct effect on the surrounding air-shed. This project was not able to sample for the durations required for standard LTO cycles. Figure 29 gives an idea of how these emissions could affect the global atmosphere.

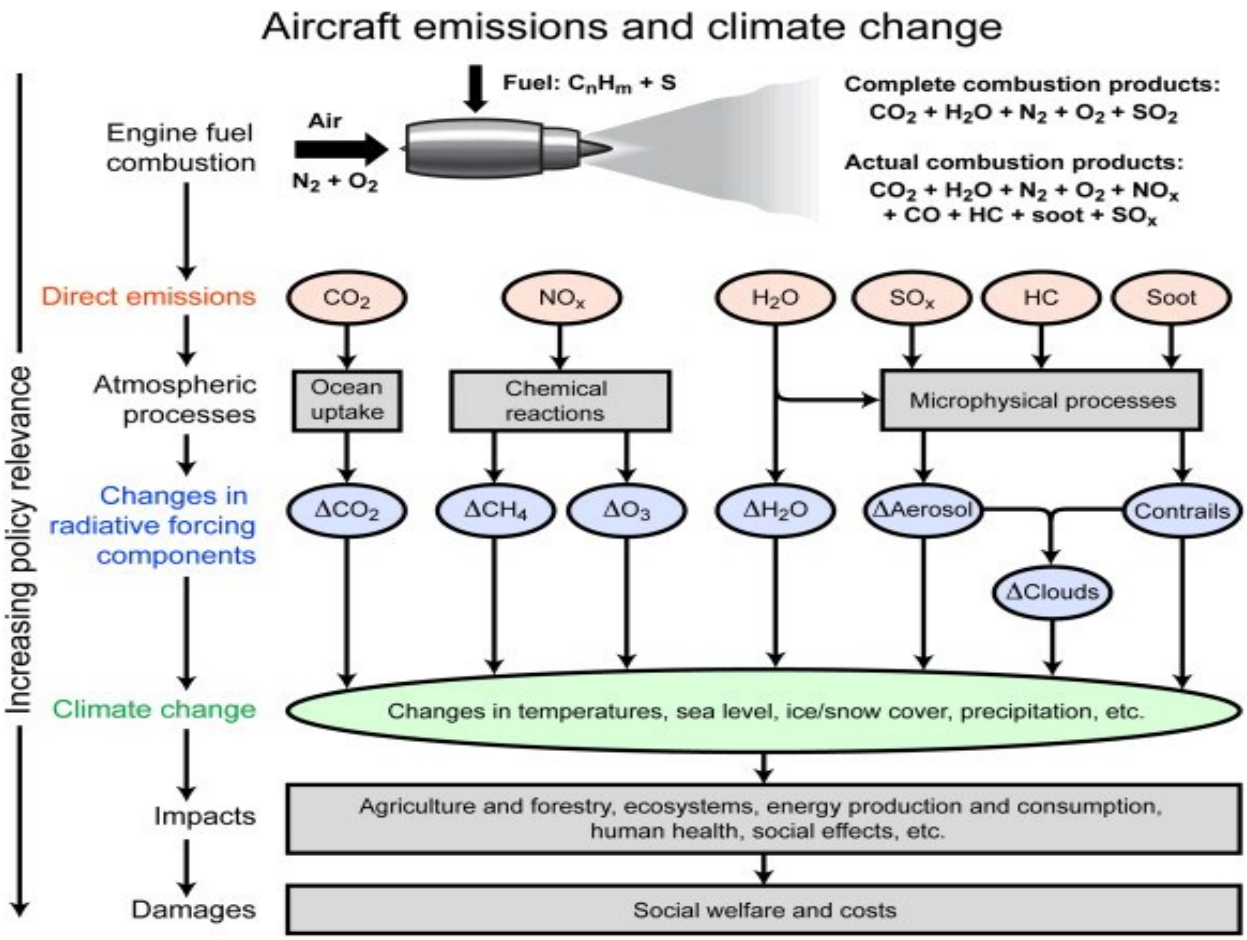

Figure 29. Aircraft Emissions and Climate Change [47]

4. Concluding Remarks

The initial goal of this research was to develop a consistent method of sampling gas turbine emissions using current in-house equipment. This goal was chosen to help advance the development of biojet fuel production at the University of Kansas. By having a consistent small-batch sampling procedure in place, future exhaust emission research can be combined with chemical composition information to develop an alternative fuel with minimal environmental impact. A Semtech-DS analyzer was our best in-house option for collecting these exhaust samples. Previous work on locomotive and biodiesel emissions had been performed using the Semtech-DS portable emissions analyzer, but never any work on gas turbine or kerosene emissions. Initially there were some minor collection difficulties, such as calibration gas values, sampling set-up, and NO_x collection. Small procedural changes and accessory purchases allowed all pertinent data to be collected. If we were to know what we know now and start this project over, ideally we would purchase another gas analyzer for emissions sampling. A completely different analyzer would be beneficial, although the Semtech-DS did not show any negative indicators on its ability to accurately collect CO, CO_2, and THC emissions, but an additional NO or NO_2 analyzer would need to be purchased so that total NO_x concentrations could be gathered simultaneously. Also, a method to sample PM concentrations and speciation would be useful to further quantify environmental and air quality impacts. Along with use of an additional gaseous analyzer, chemical composition profiles of the base fuels (Jet A, HRJ, and FT) and each fuel blend would be useful when deciphering the emission results as our results suggest that density and cetane number are major emission concentration factors.

Other research studies reported have been large-scale multi-group sampling trips with very specific instrumentation and equipment. These studies are often very extensive, expensive,

and time consuming. We were able to accomplish small batch-scale testing that will prove very useful for future research at the University of Kansas. Baseline data was collected on conventional Jet A emissions from a PT6 turboprop gas turbine engine. Good reproducibility and run-to-run variability was observed for our sampling procedure. Improvements to the probe stand could be made to limit the variation in probe placement in the exhaust stream and well as reduce the time spent setting-up. However, this was not a major issue as long as attention was paid to its placement during each testing run. Emission data on two alternative fuels, a hydroprocessed renewable jet from tallow and a Sasol IPK Fischer-Tropsch, were also gathered during the latter half of our testing dates. These testing sessions showed good repeatability but a larger variation of some pollutant concentrations, mainly HC and NO_2. This information and research will also prove useful down the road when future in-house alternative fuel development is further along and ready for testing in a gas turbine engine as a sampling procedure and reference information will already be available for comparison. Also, being able to perform relatively quick and frequent batch-scale emission sampling will be useful for knowledge on how the chemical composition of the fuel affects pollutant levels and engine performance. Overall, this project accomplished the goals it had set and was a good start for advancing the viability of next generation alternative aviation fuels at the University of Kansas.

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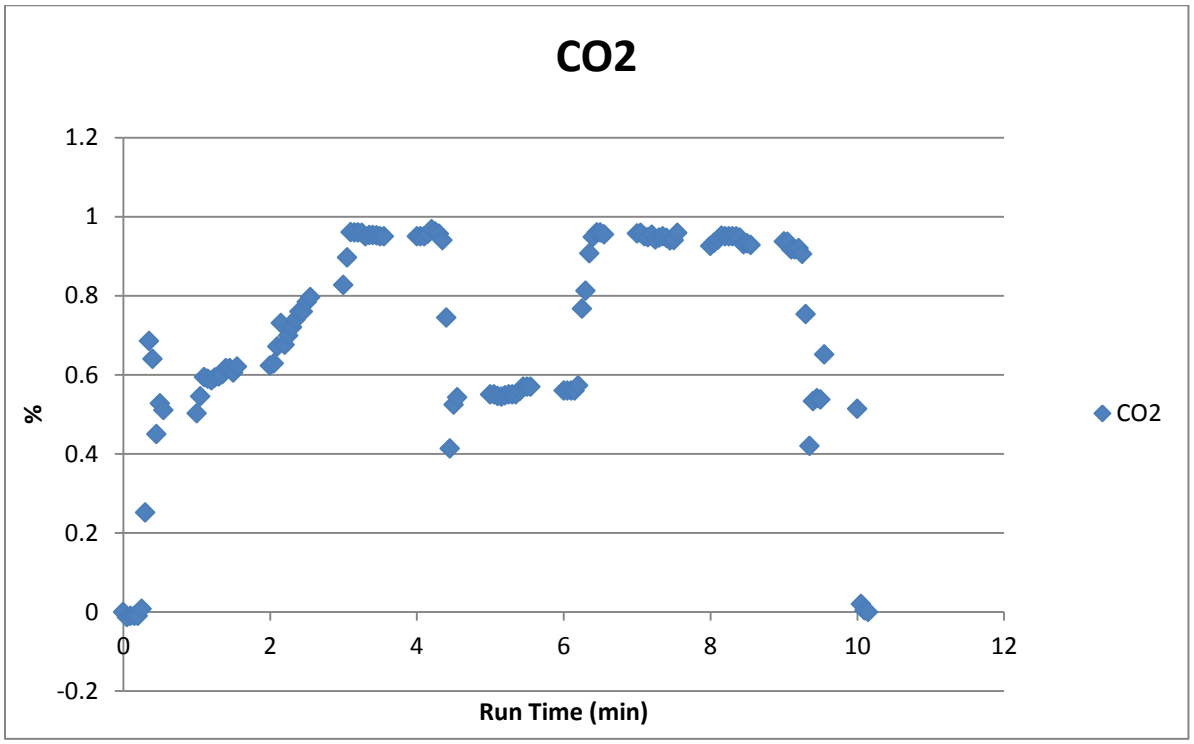
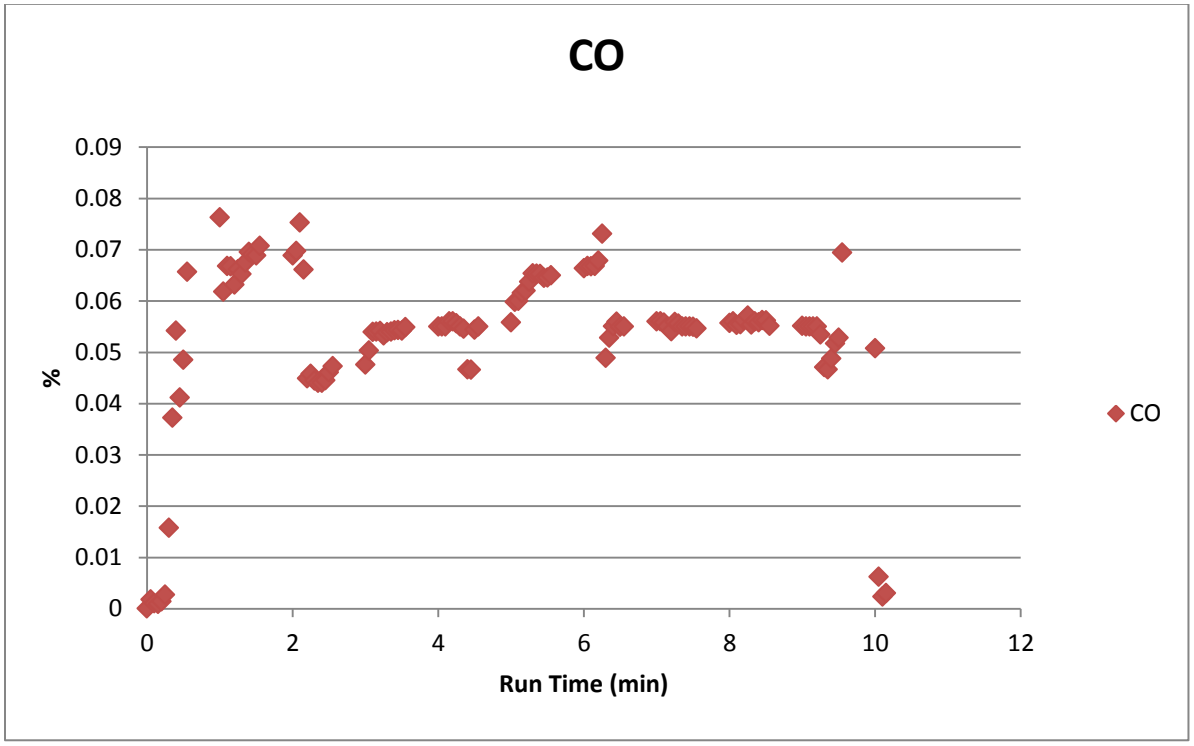
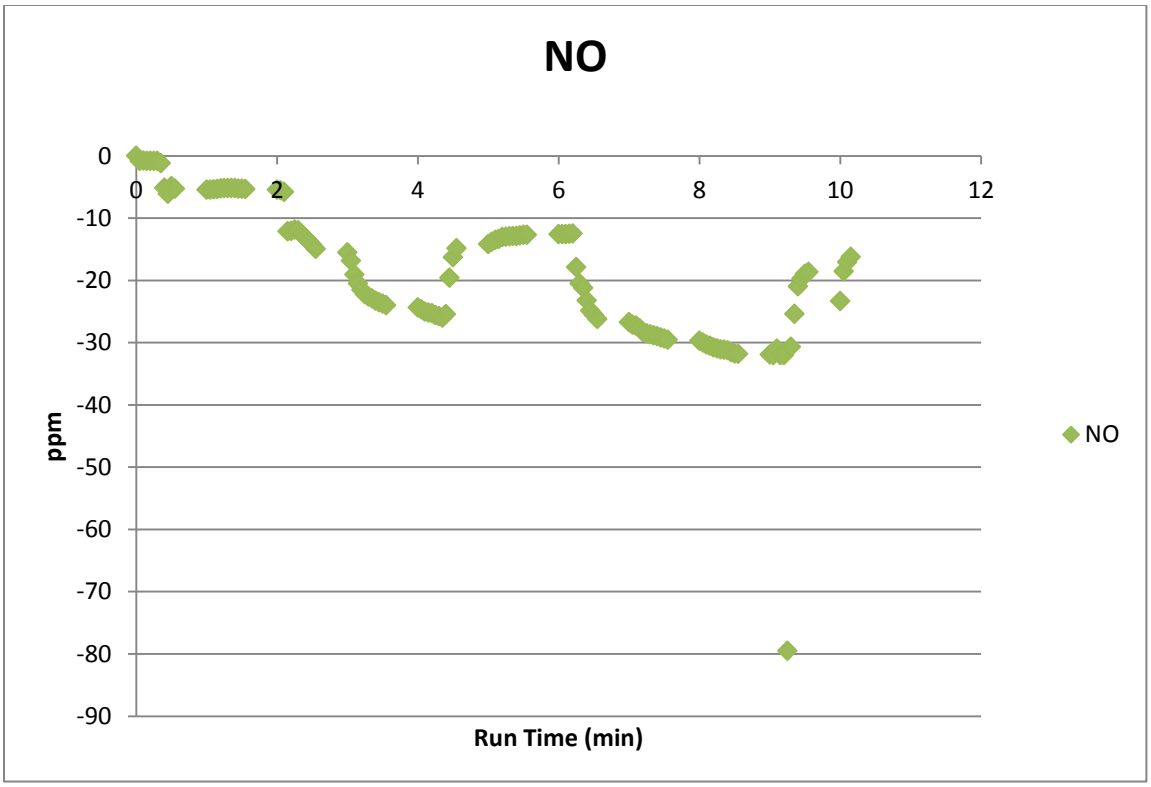
Appendix A: Olympus HP Sampling Results

Baseline 5/3/2011 Olympus HP



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2
4
6
8
10
12
ppm
Run Time (min)
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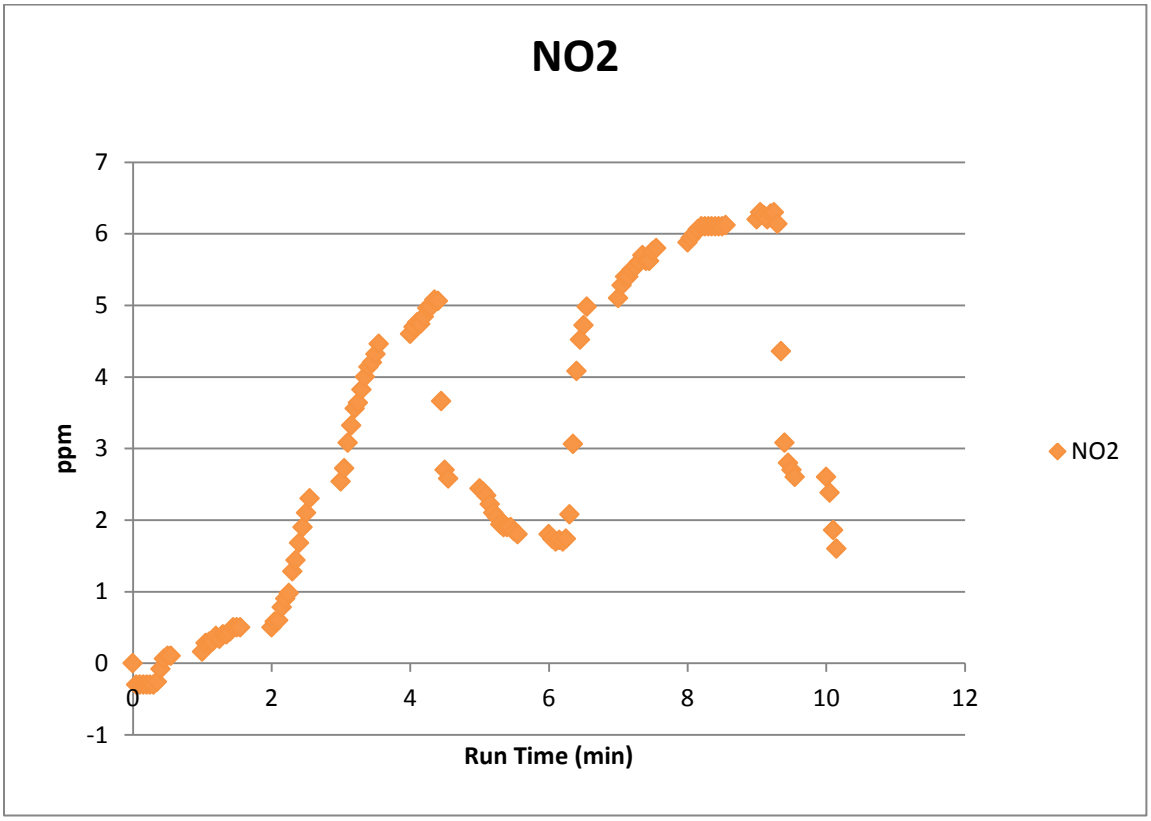
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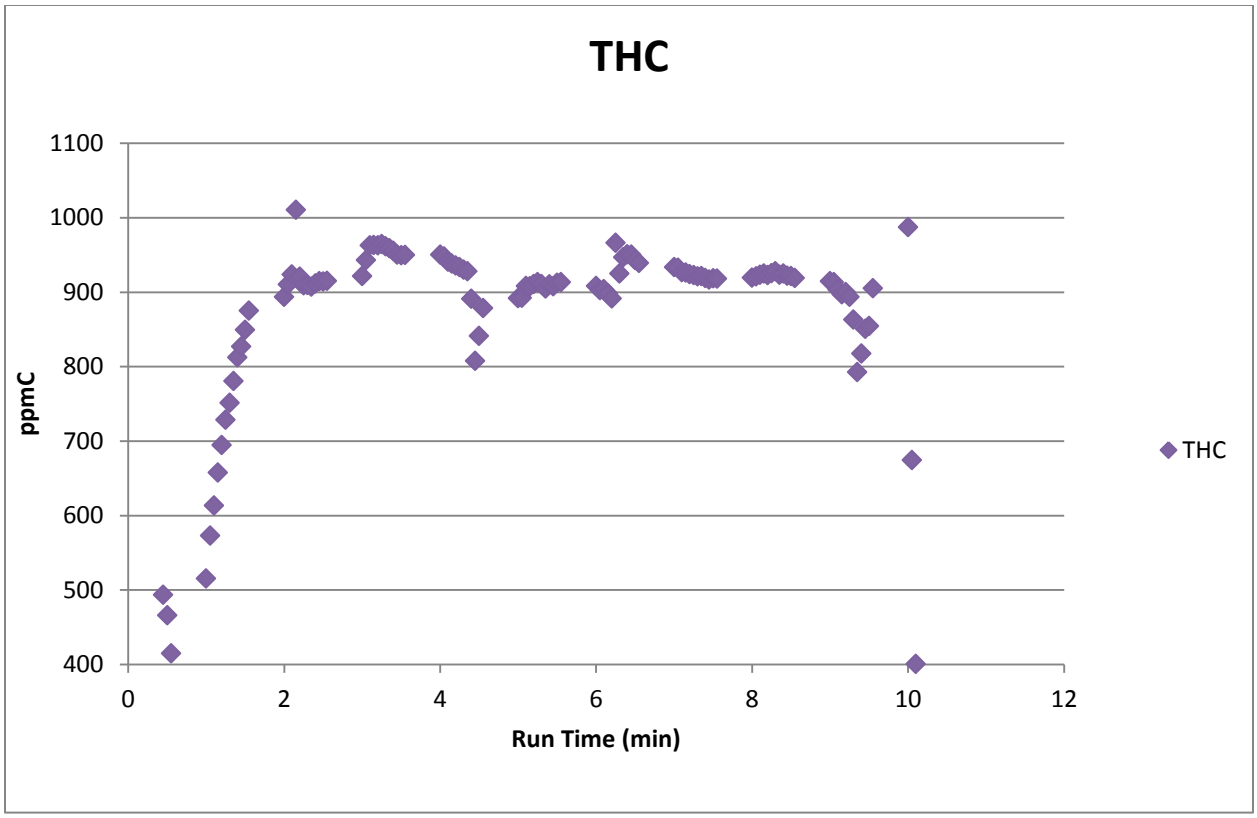
8
10
12
ppm
Run Time (min)
NO2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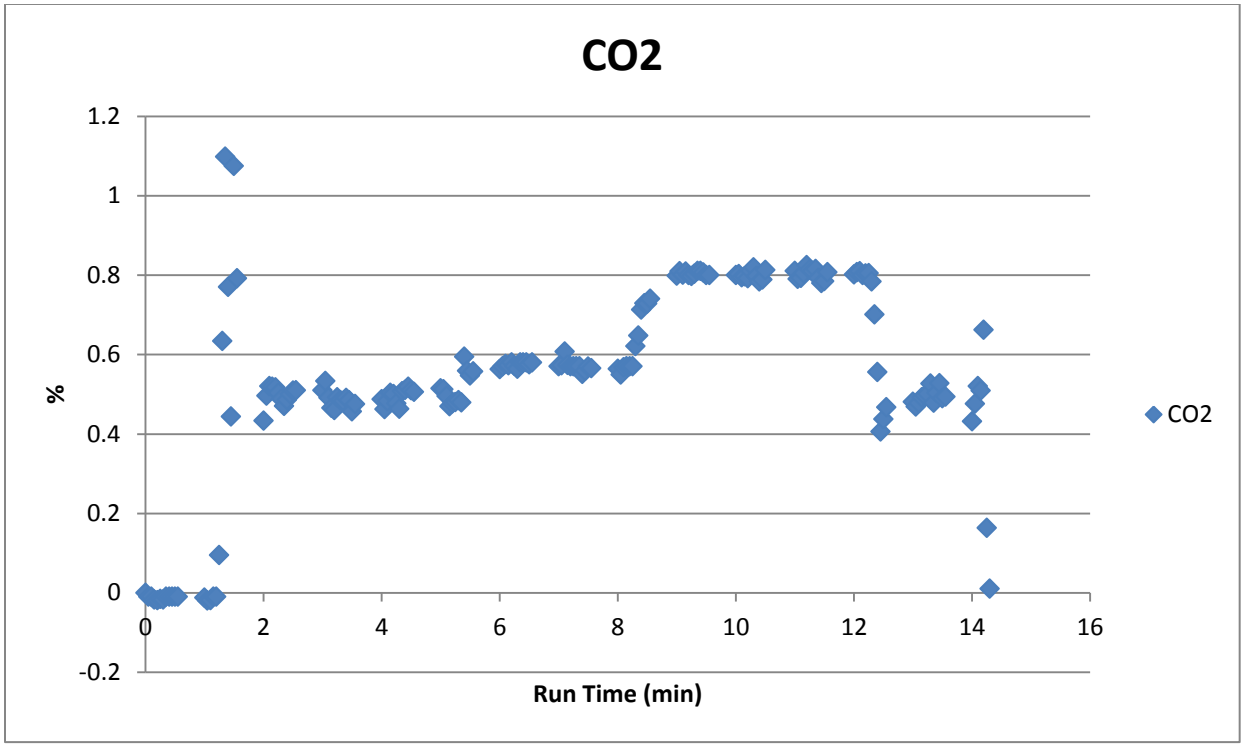
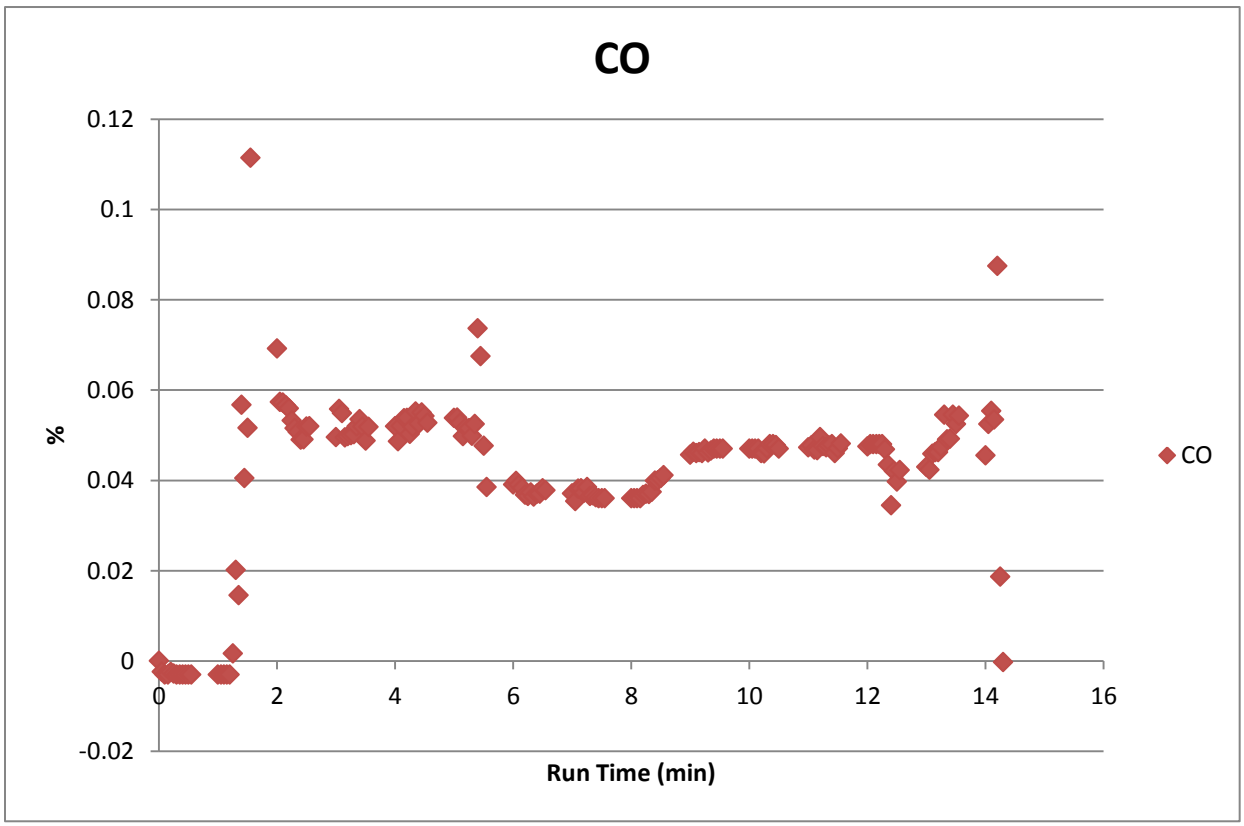
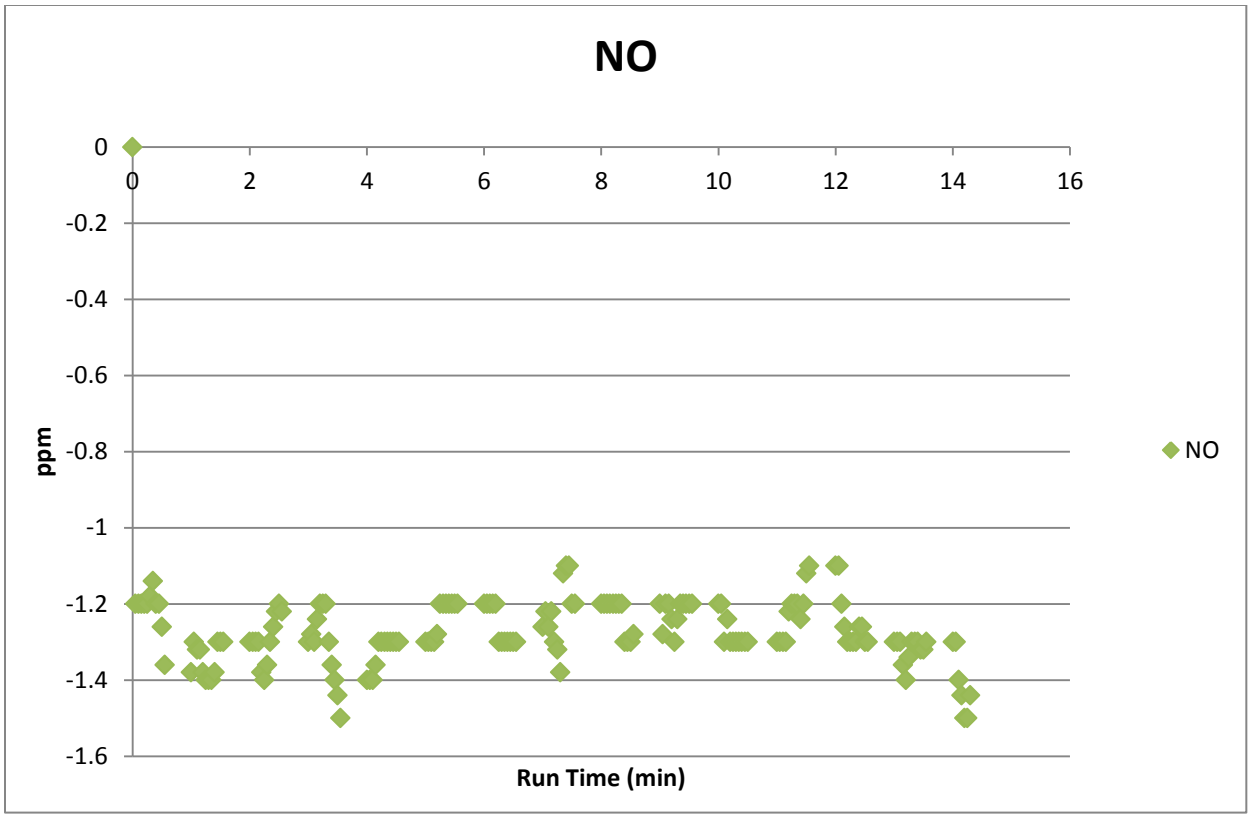
Run Time (min)
THC

ByMyself 7/26/2011Olympus HP



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8
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12
14
16
Run Time (min)
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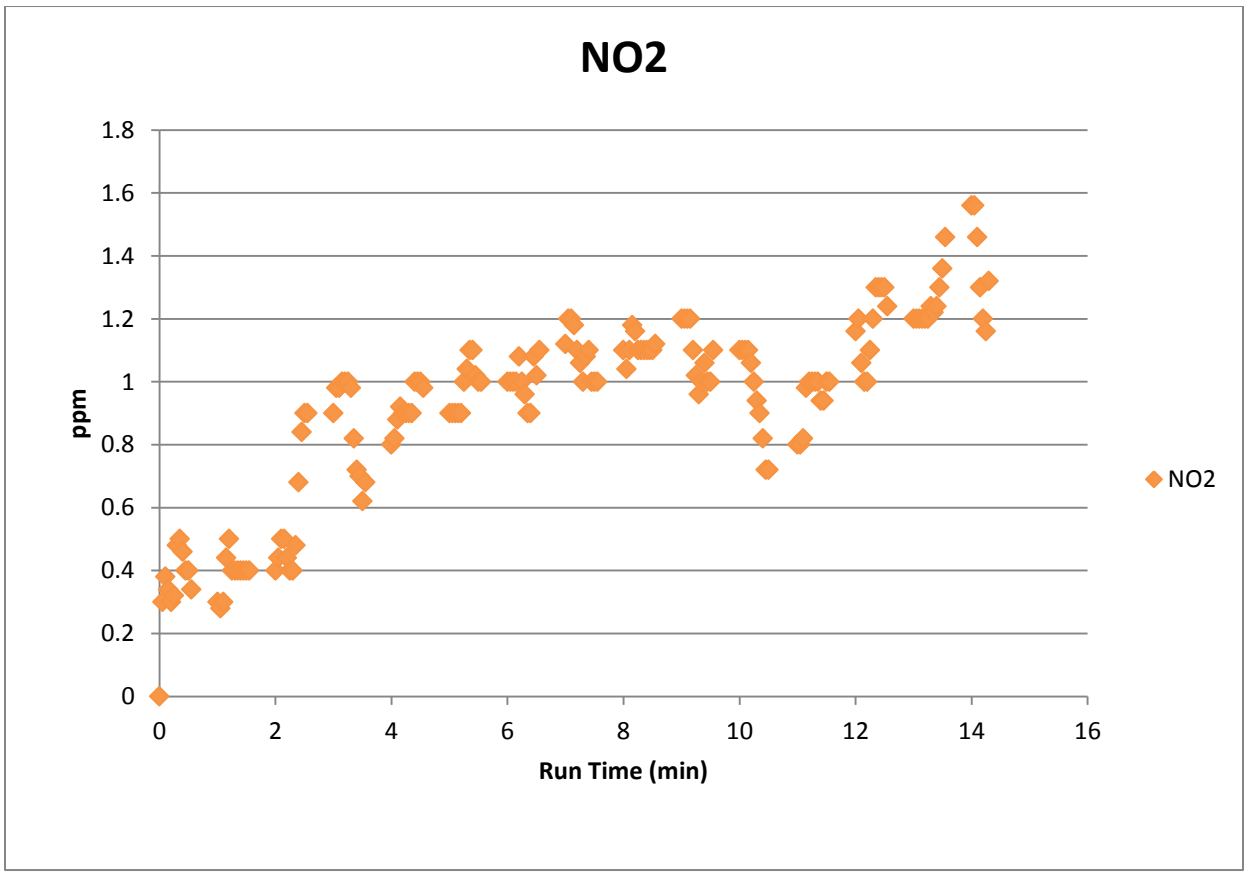
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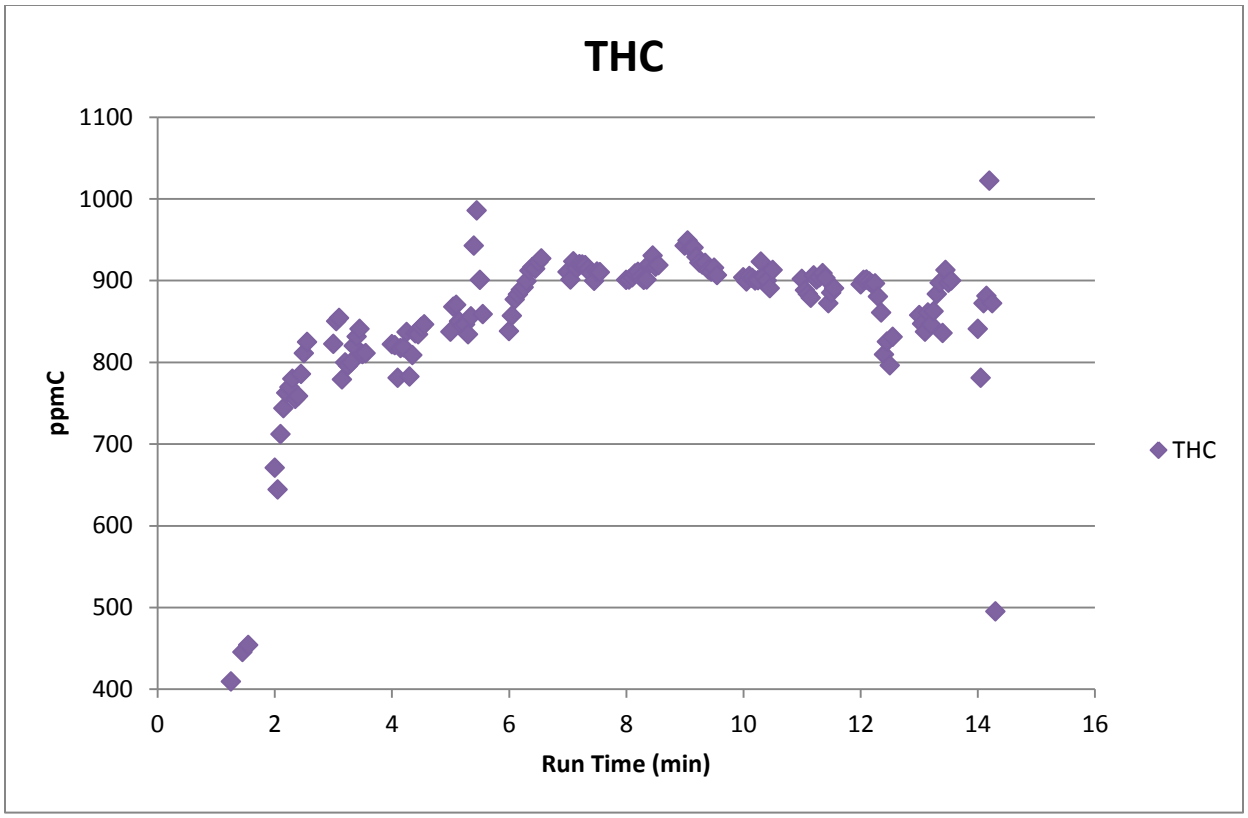
Run Time (min)
NO2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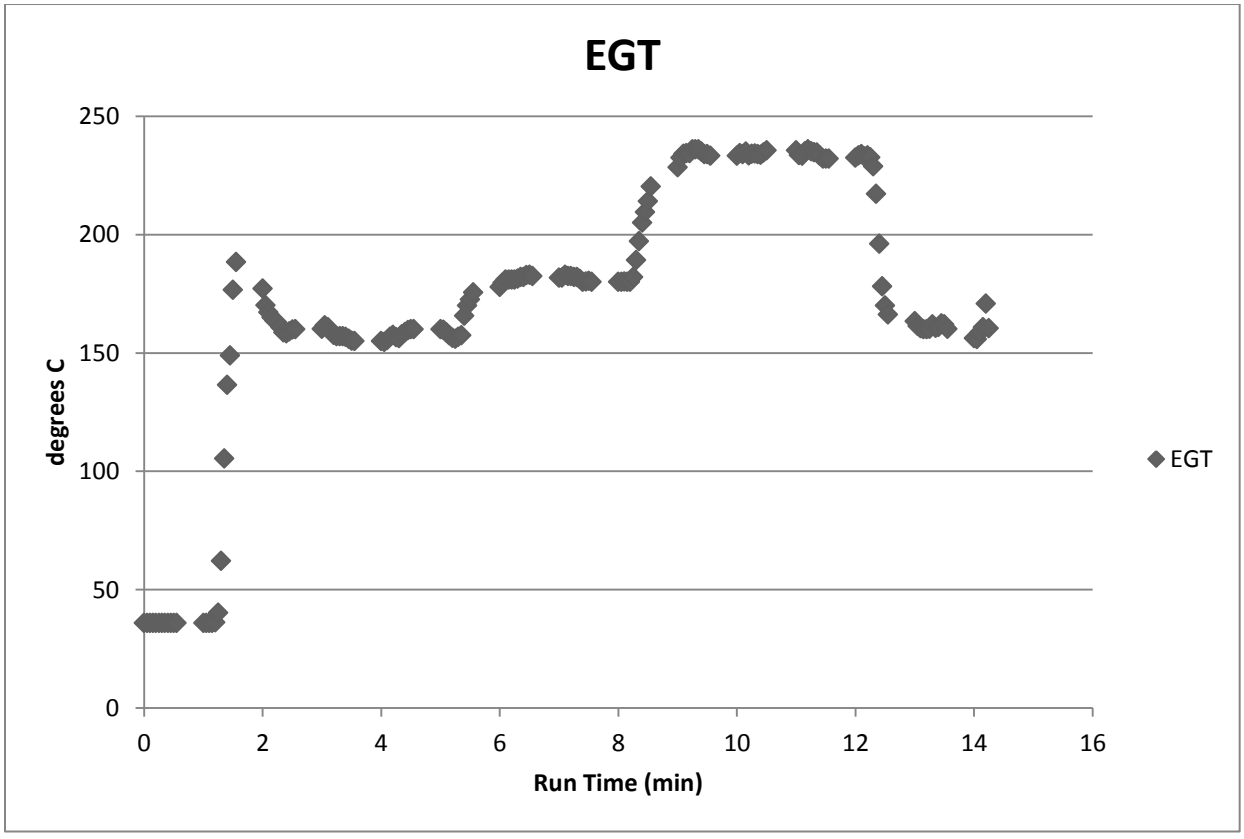
Run Time (min)
THC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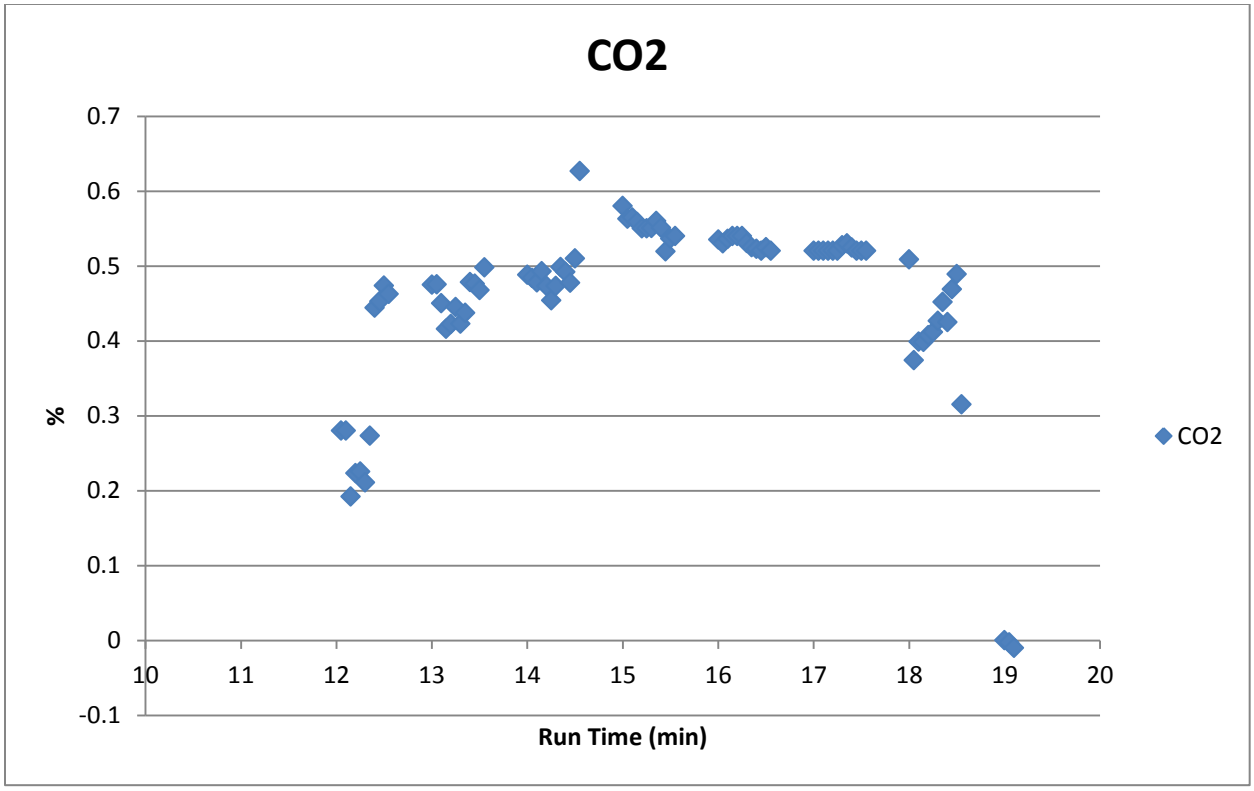
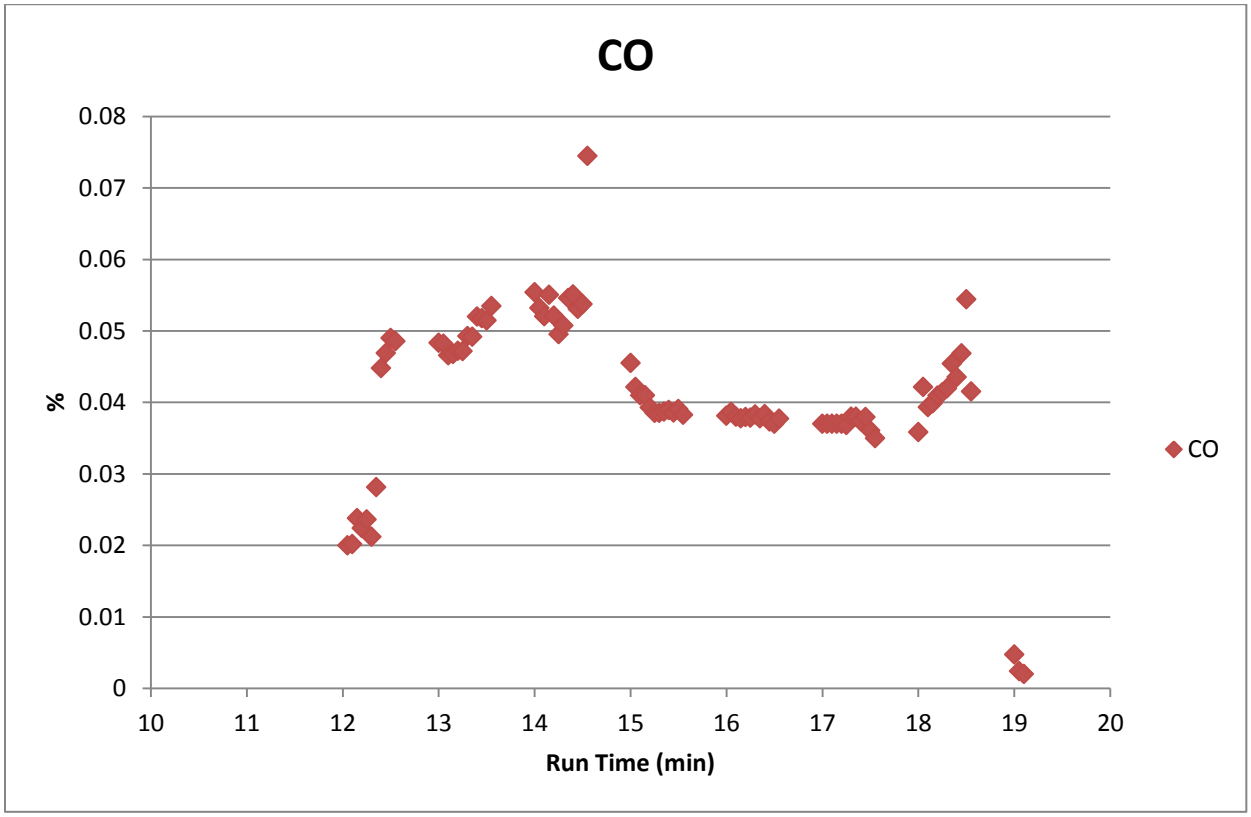
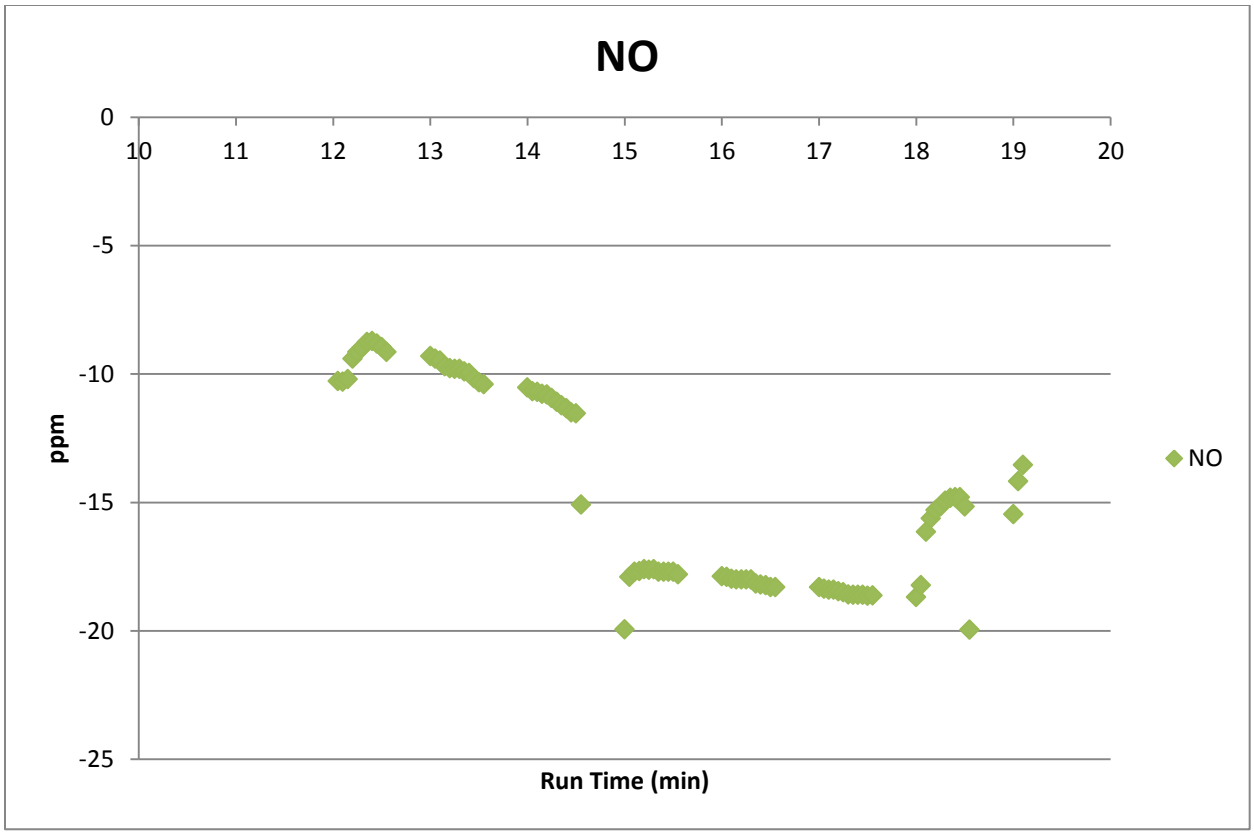
Run Time (min)
EGT

HalfOil 3ft 9/9/2011 Olympus HP



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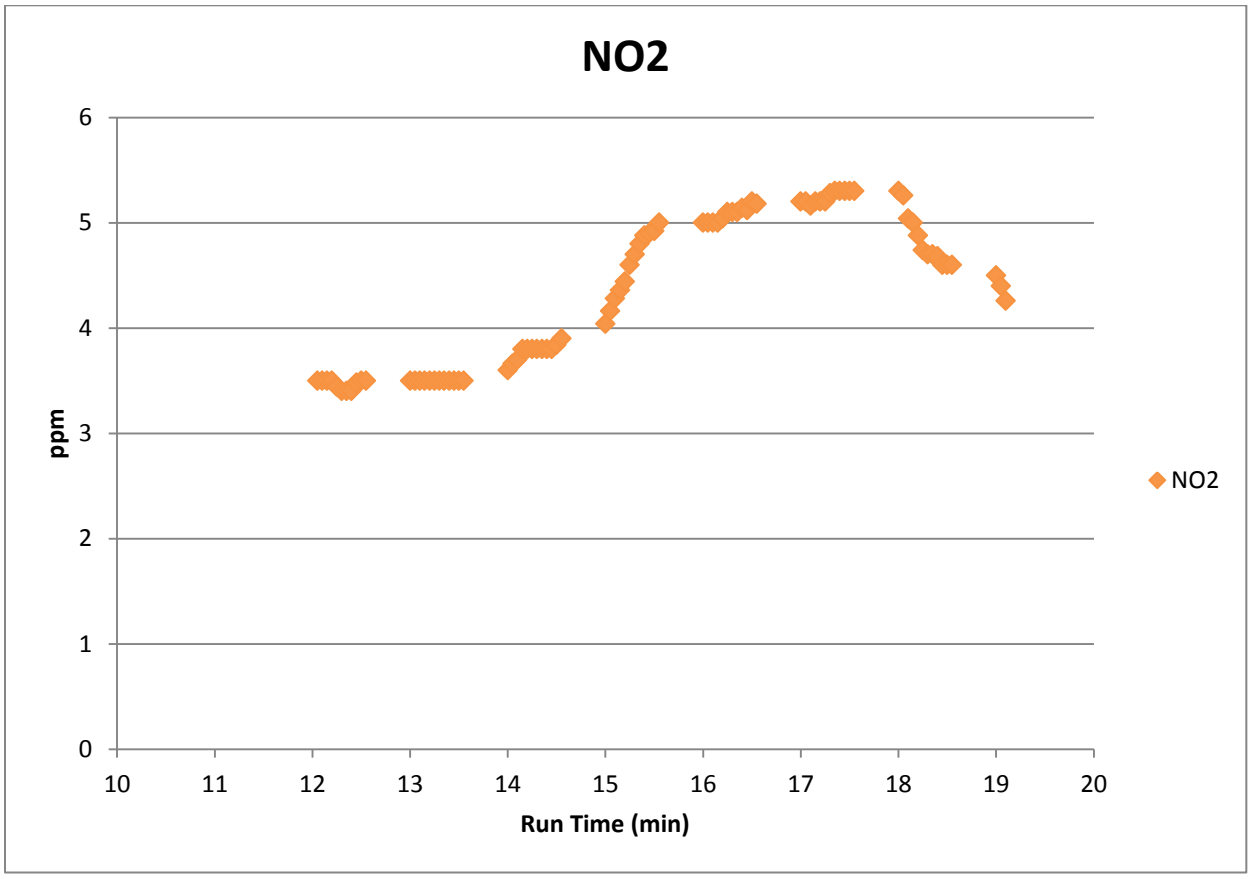
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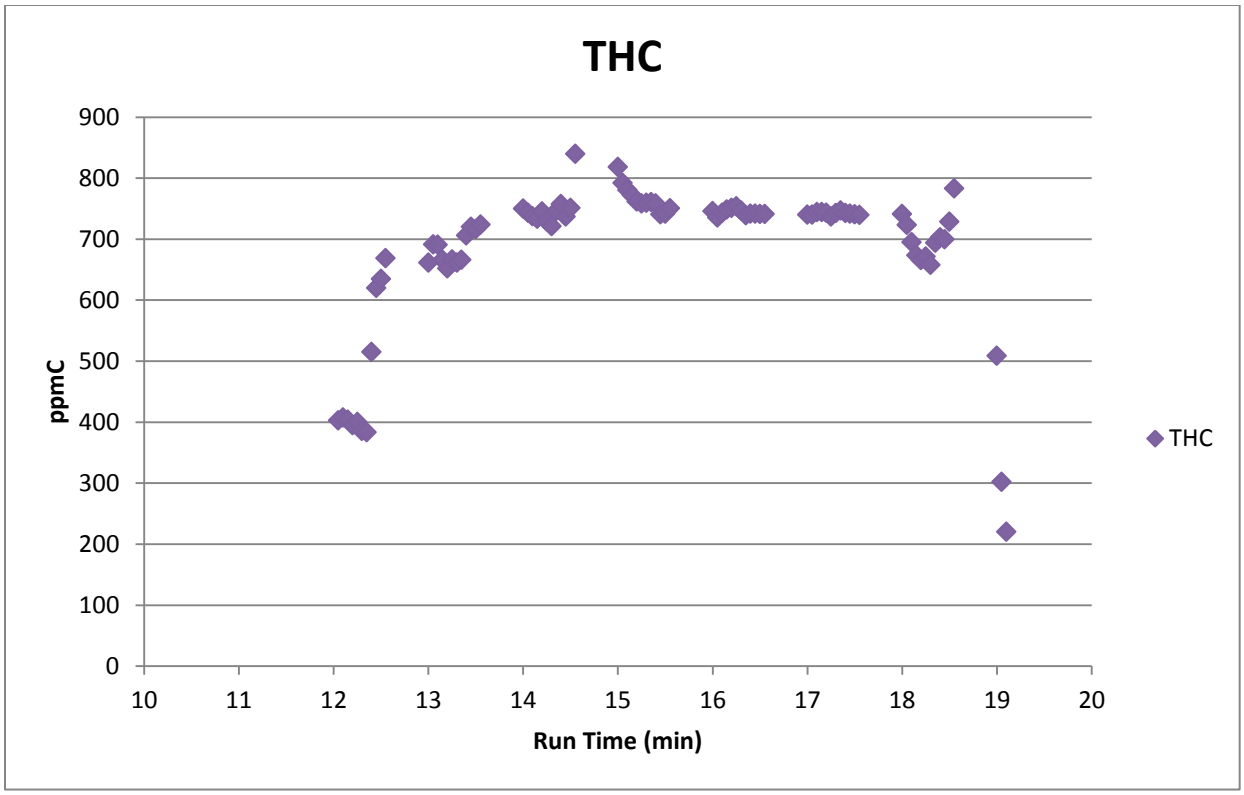
Run Time (min)
NO2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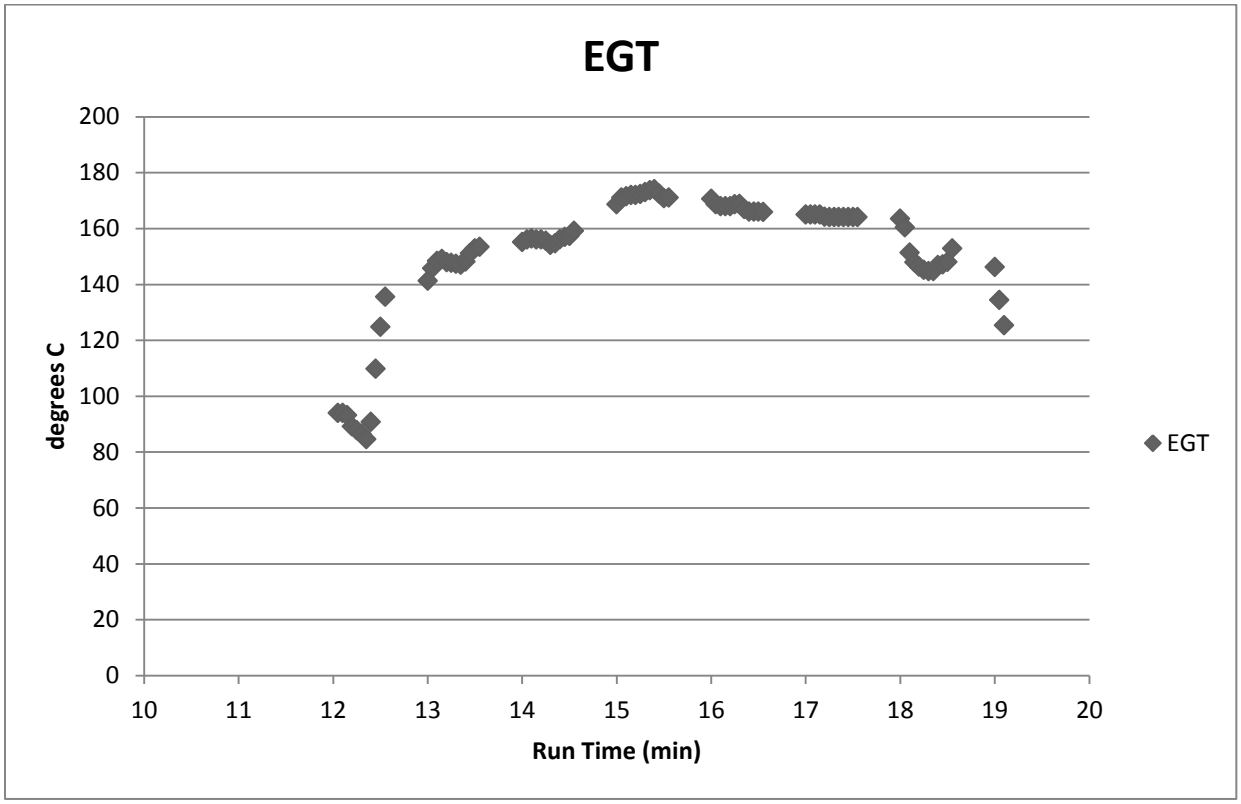
Run Time (min)
THC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Run Time (min)
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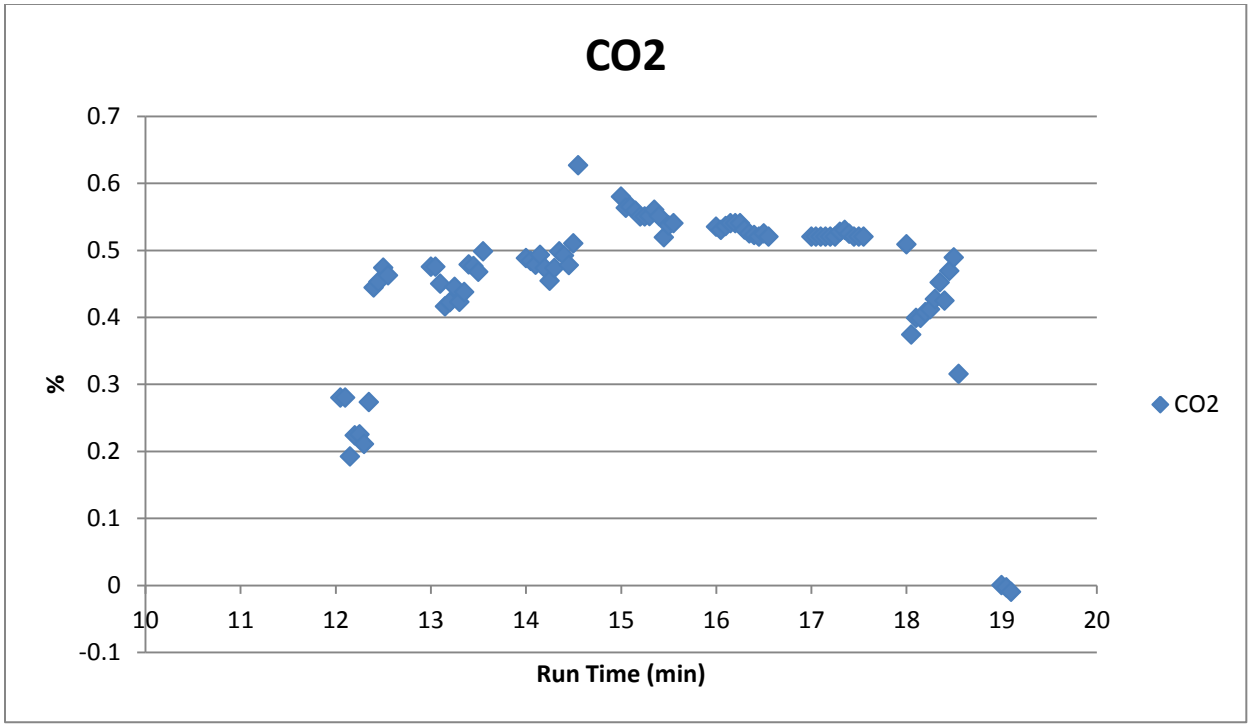
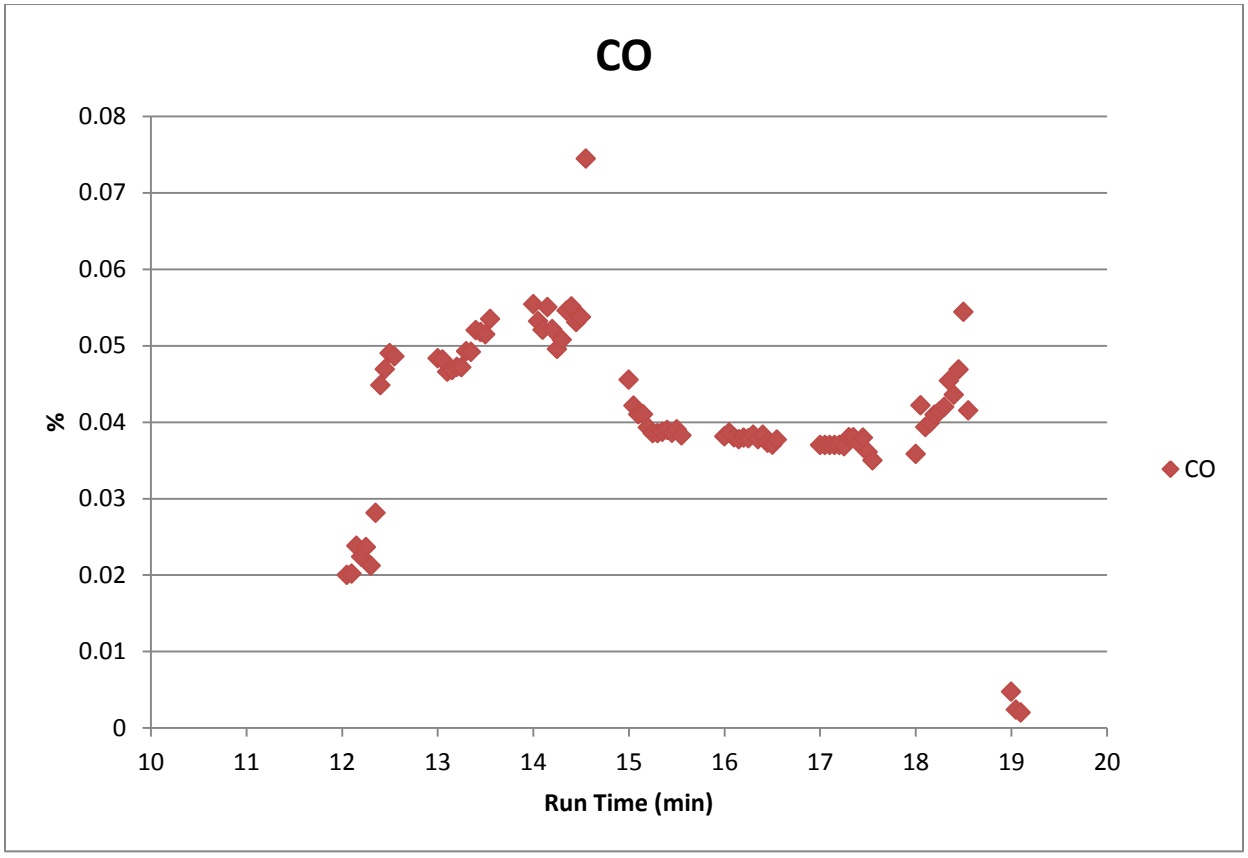
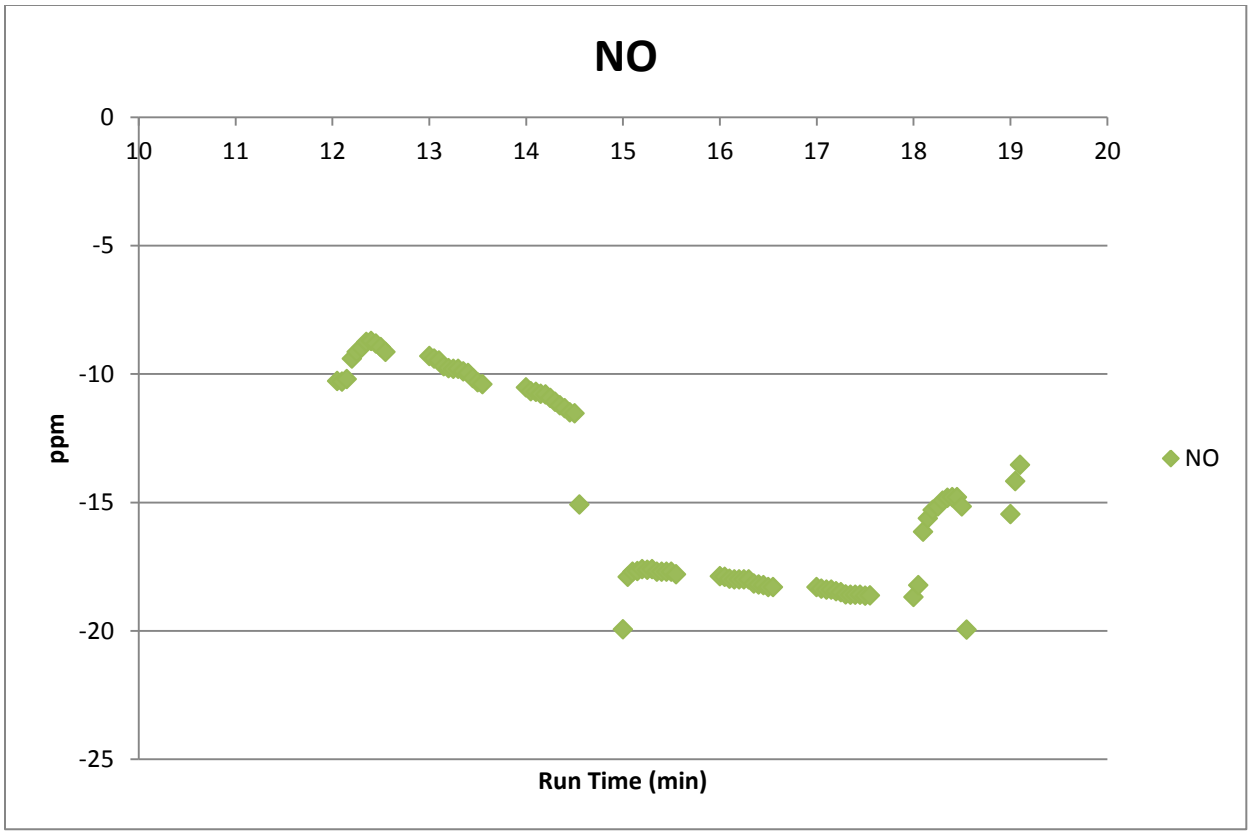
HalfOil 6ft 9/9/2011 Olympus HP



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Run Time (min)
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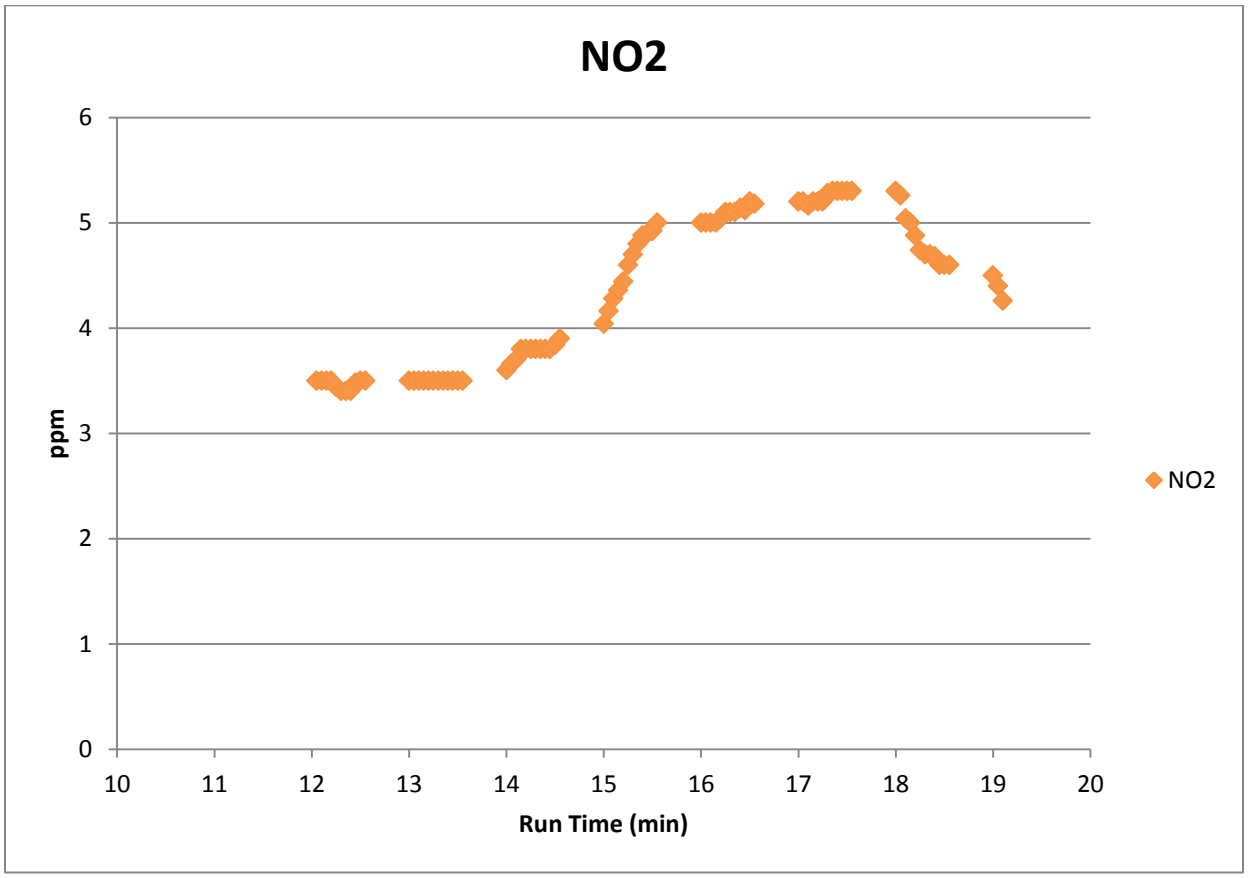
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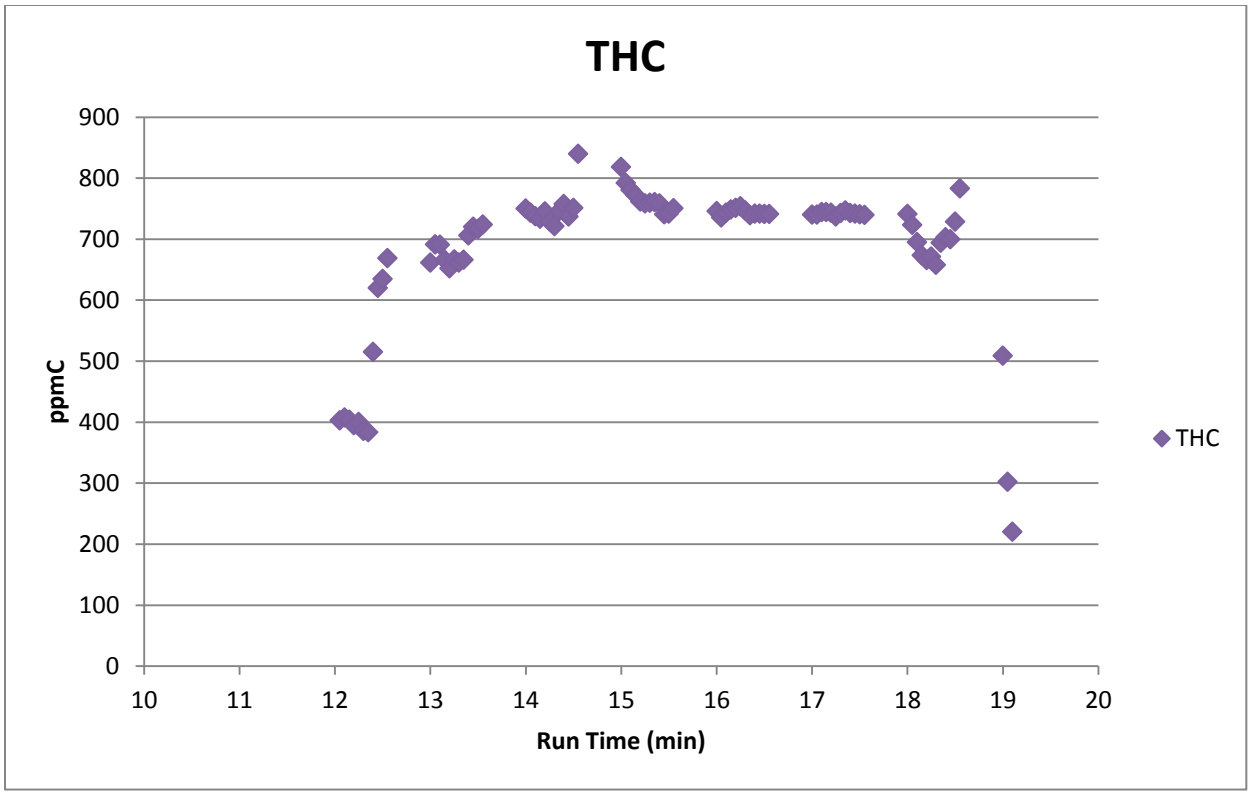
Run Time (min)
NO2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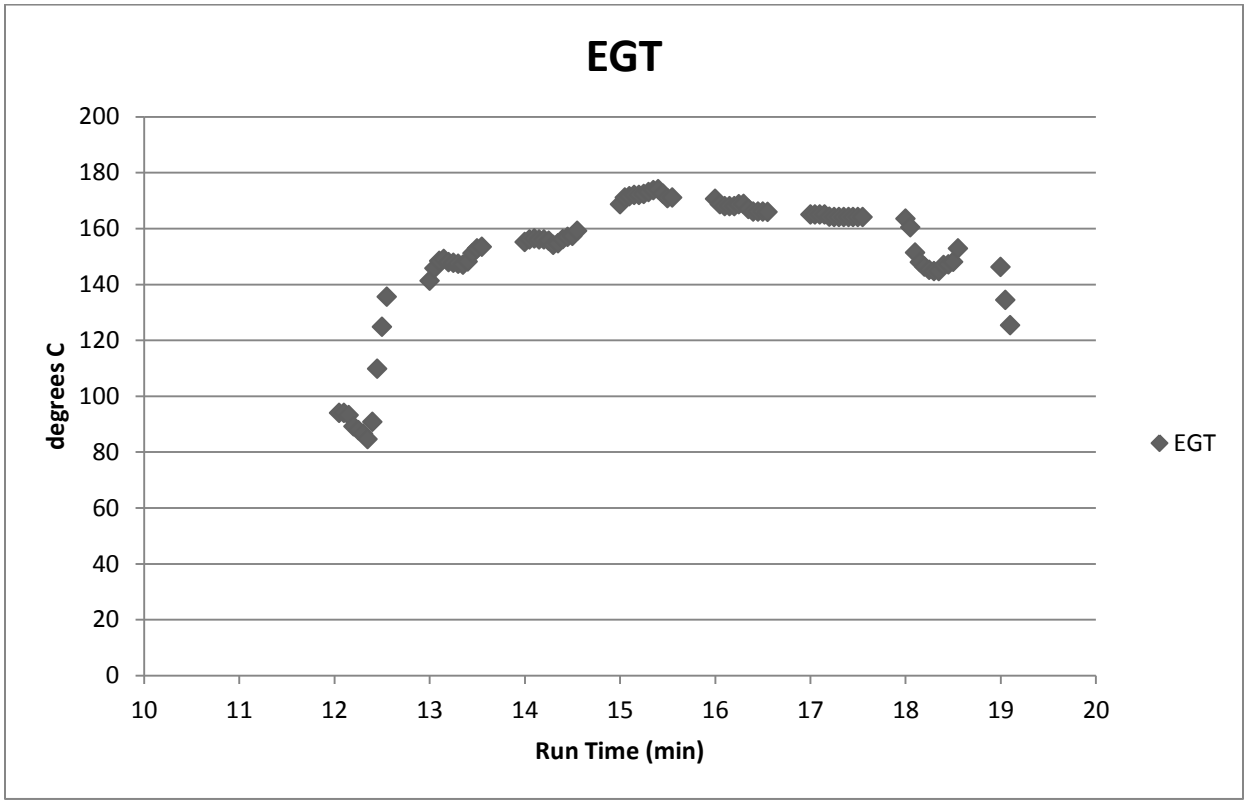
THC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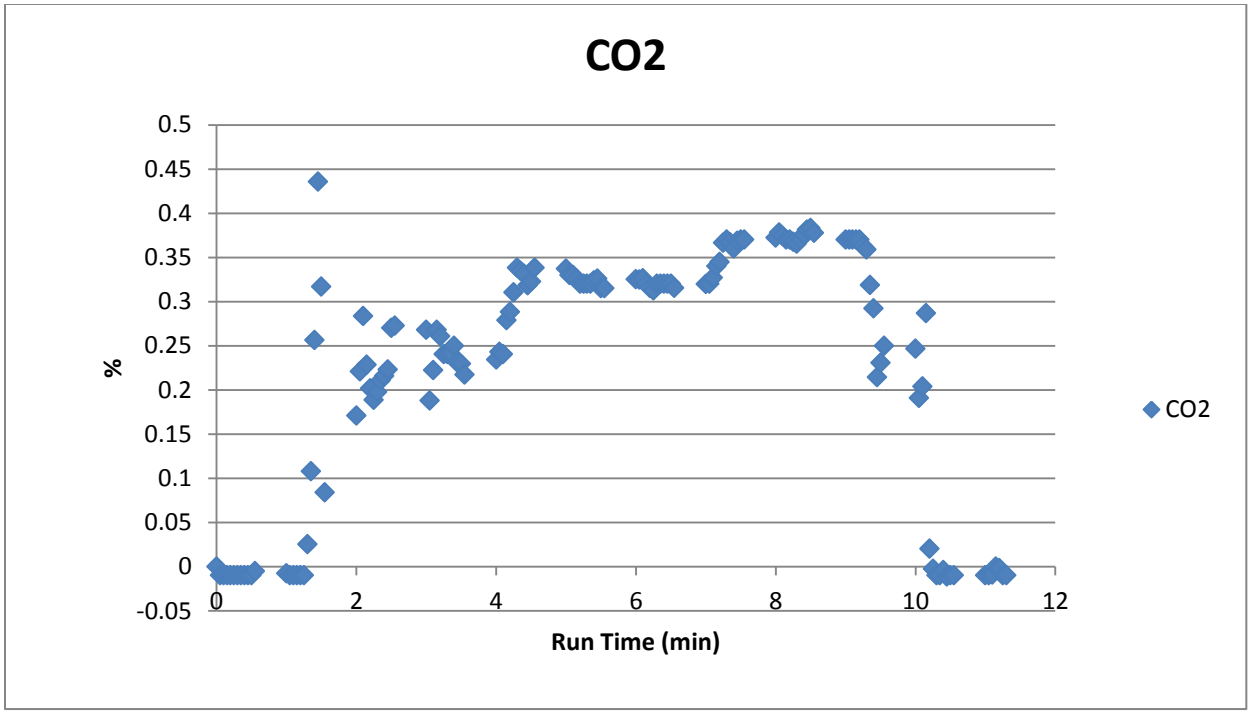
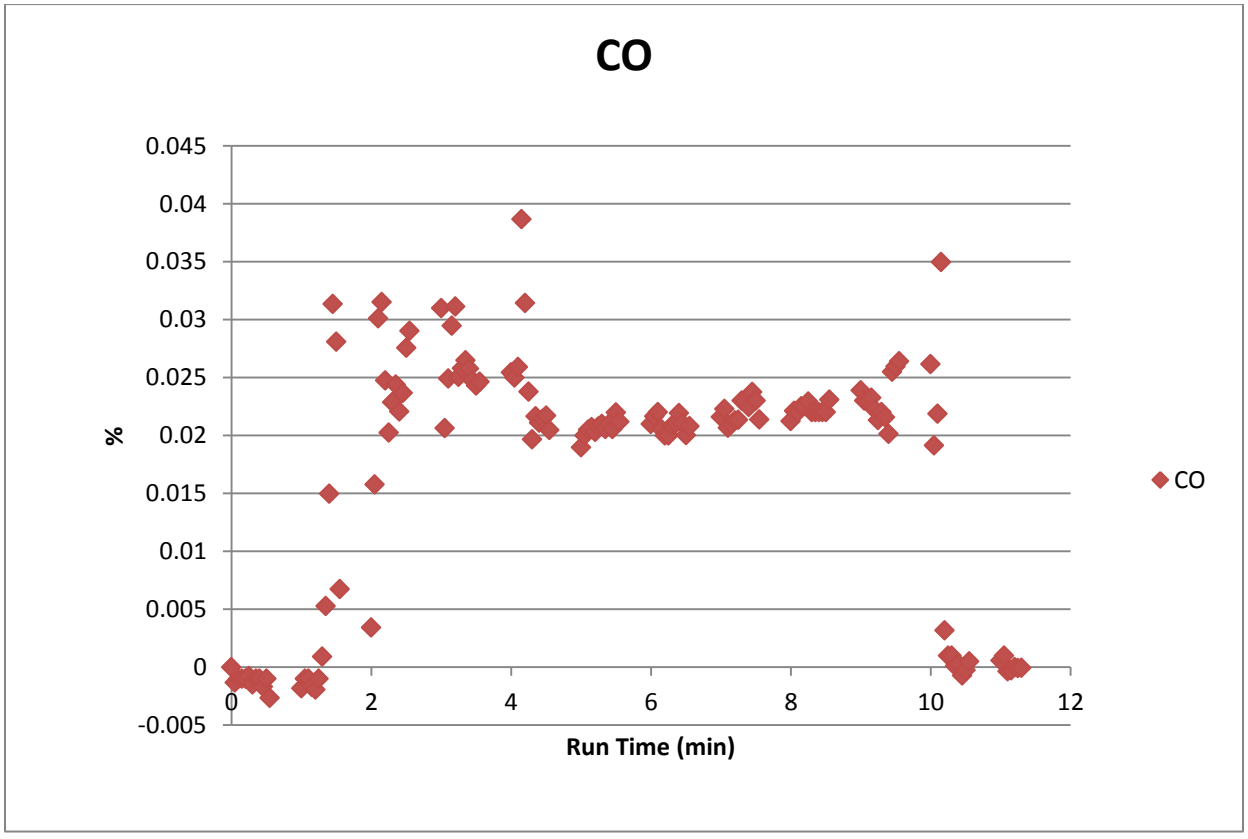
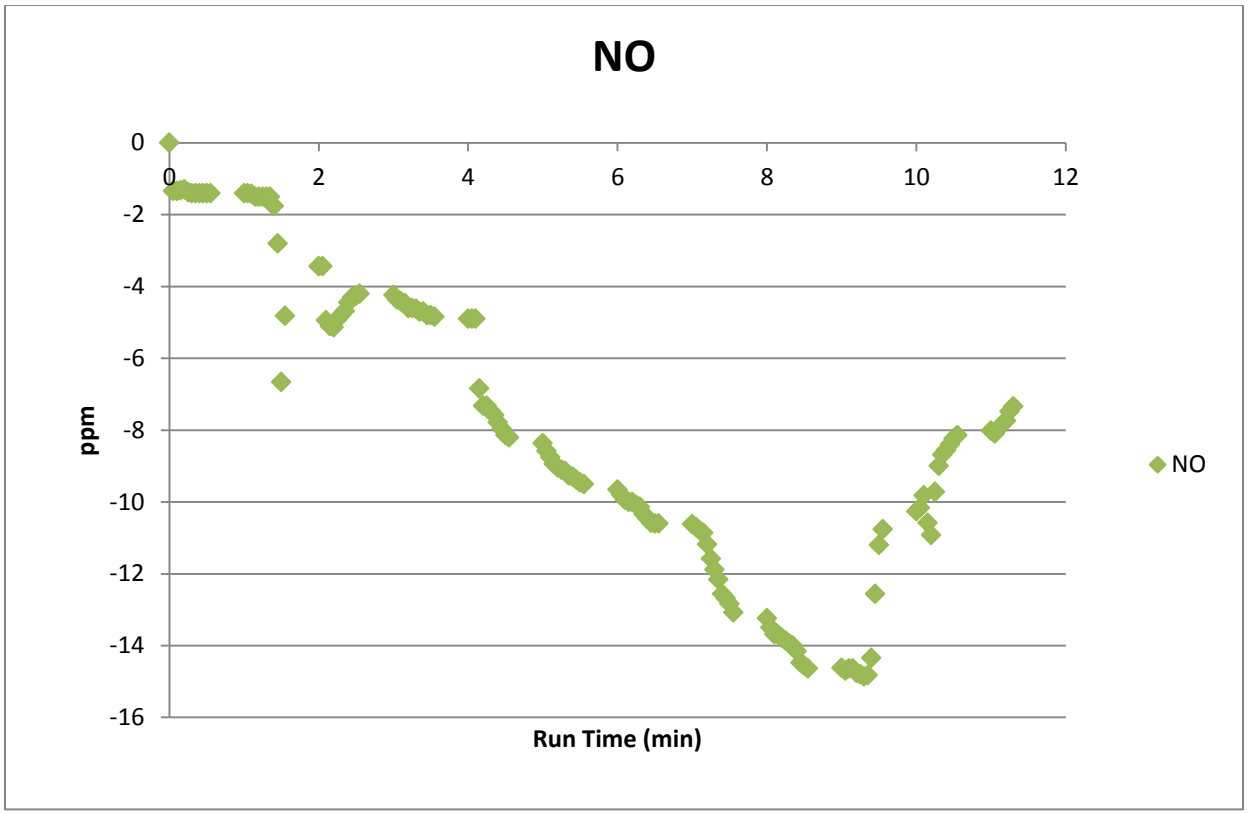
80
60
40
20
0
degrees C
10
11
12
13
14
15
16
17
18
19
20
Run Time (min)
EGT

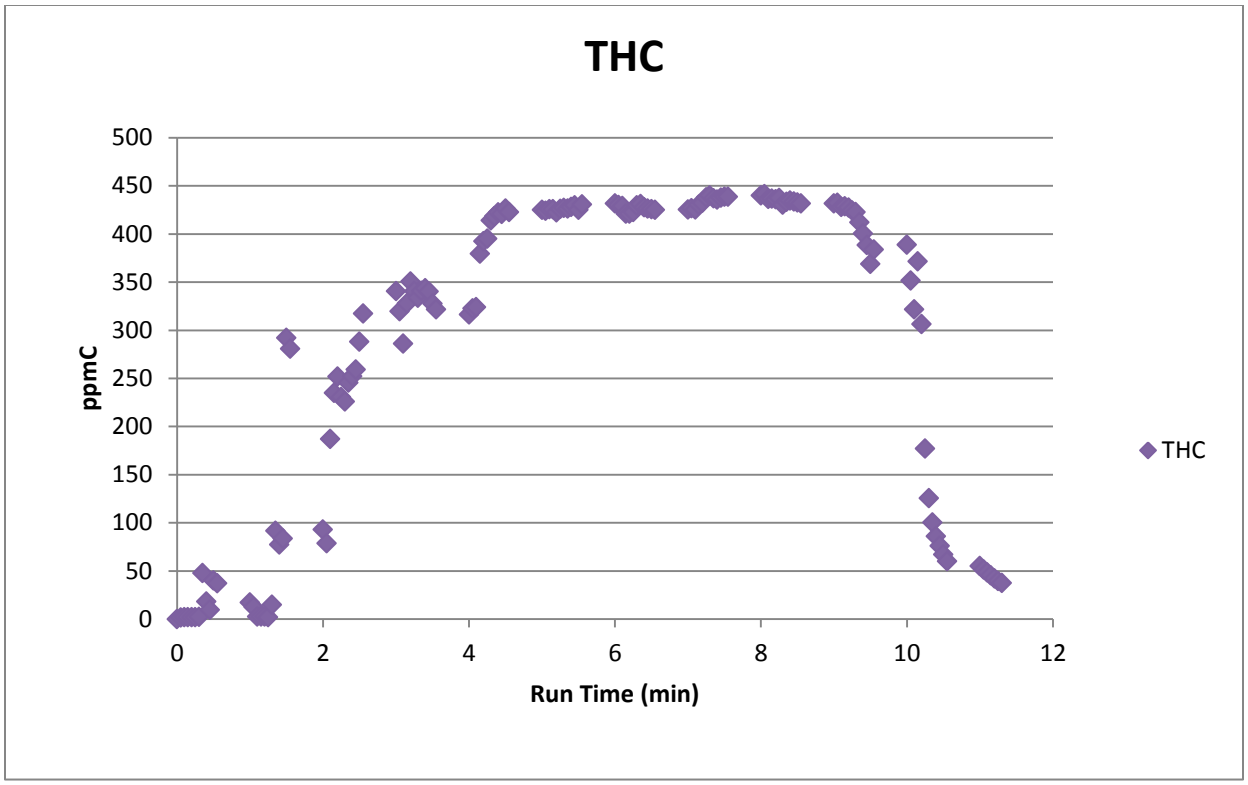
HalfOil 6ft 9/13/2011 Olympus HP

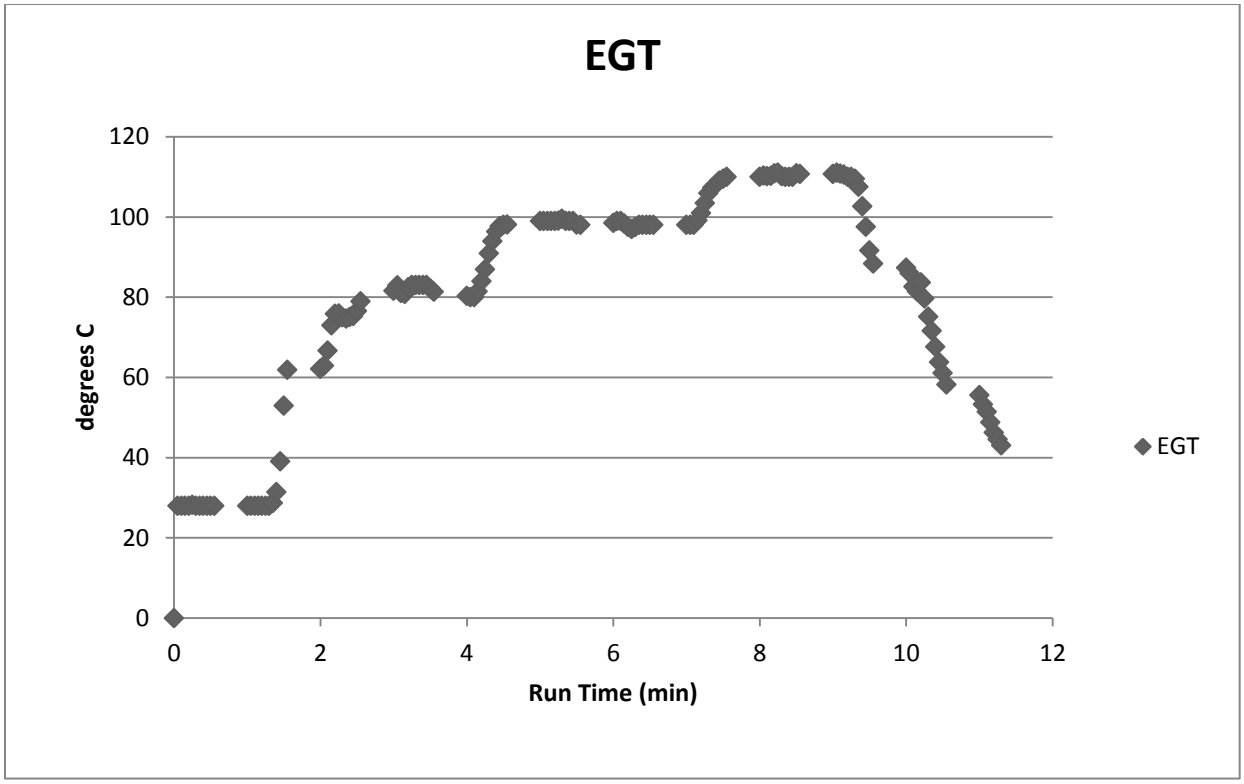




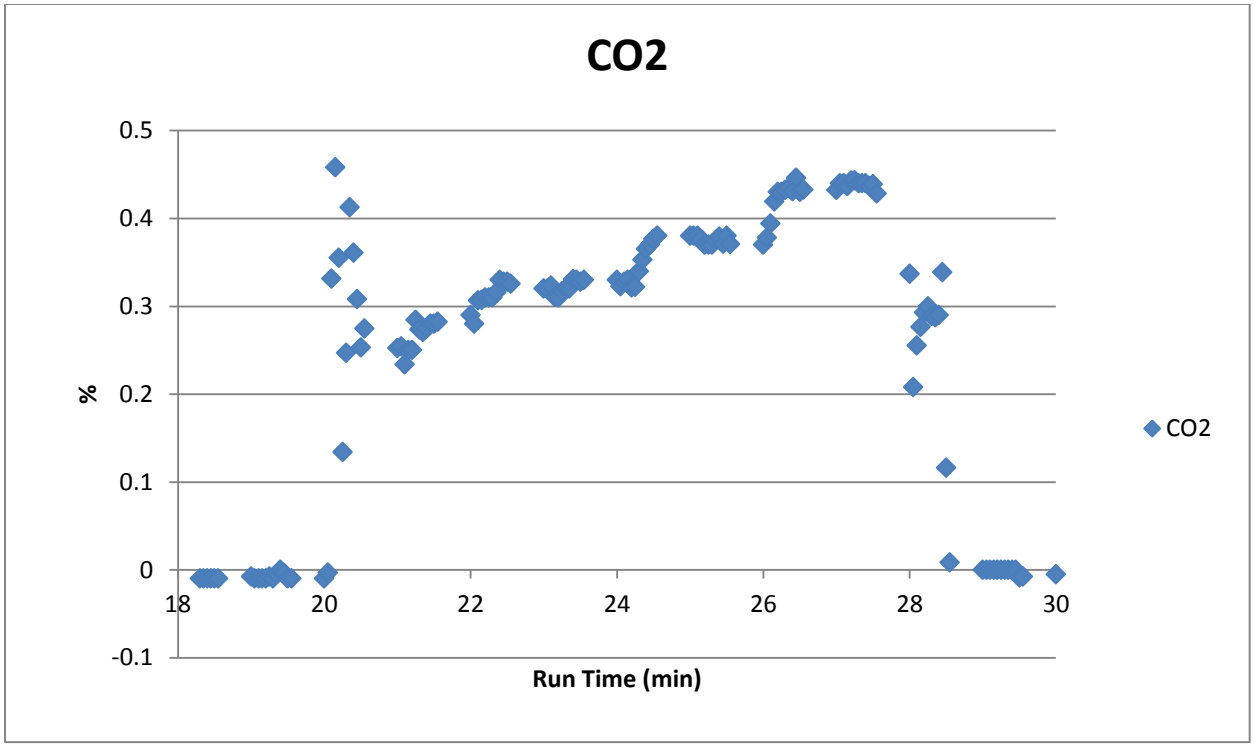

NO
0
-2
-4
-6
-8
-10
-12
-14
-16
0
2
4
6
8
10
12
ppm
Run Time (min)
NO

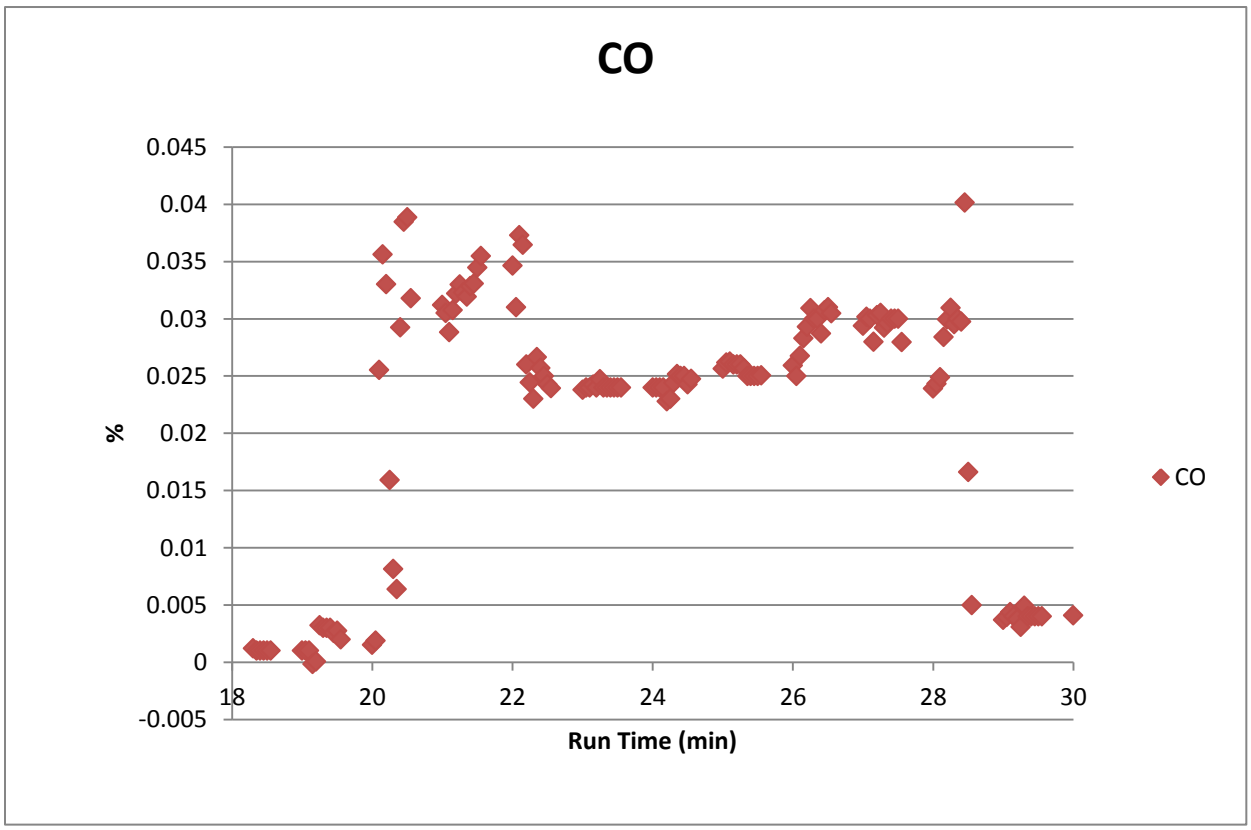

NO2
6
5
4
3
2
1
0
0
2
4
6
8
10
12
ppm
Run Time (min)
NO2

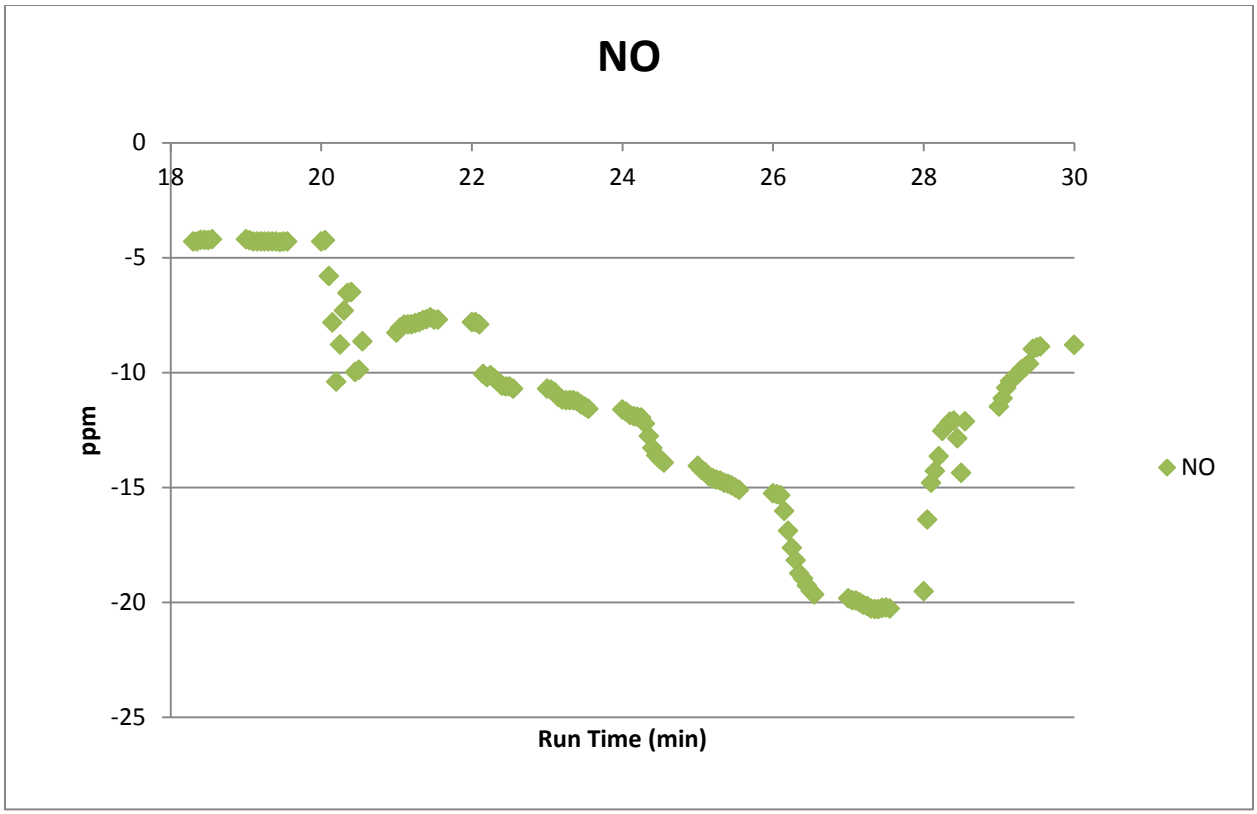

THC
ppmC
500
450
400
350
300
250
200
150
100
50
0
0
2
4
6
8
10
12
Run Time (min)
THC

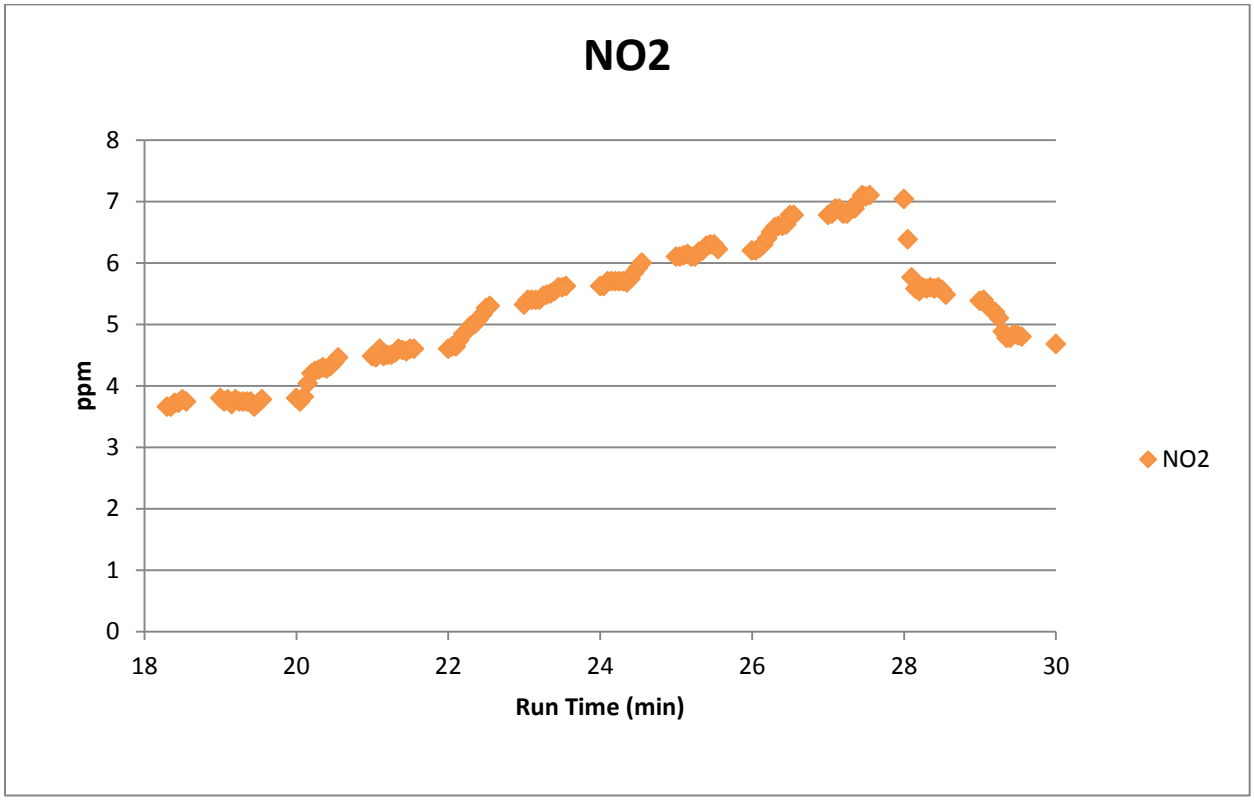

EGT
degrees C
120
100
80
60
40
20
0
0
2
4
6
8
10
12
Run Time (min)
EGT

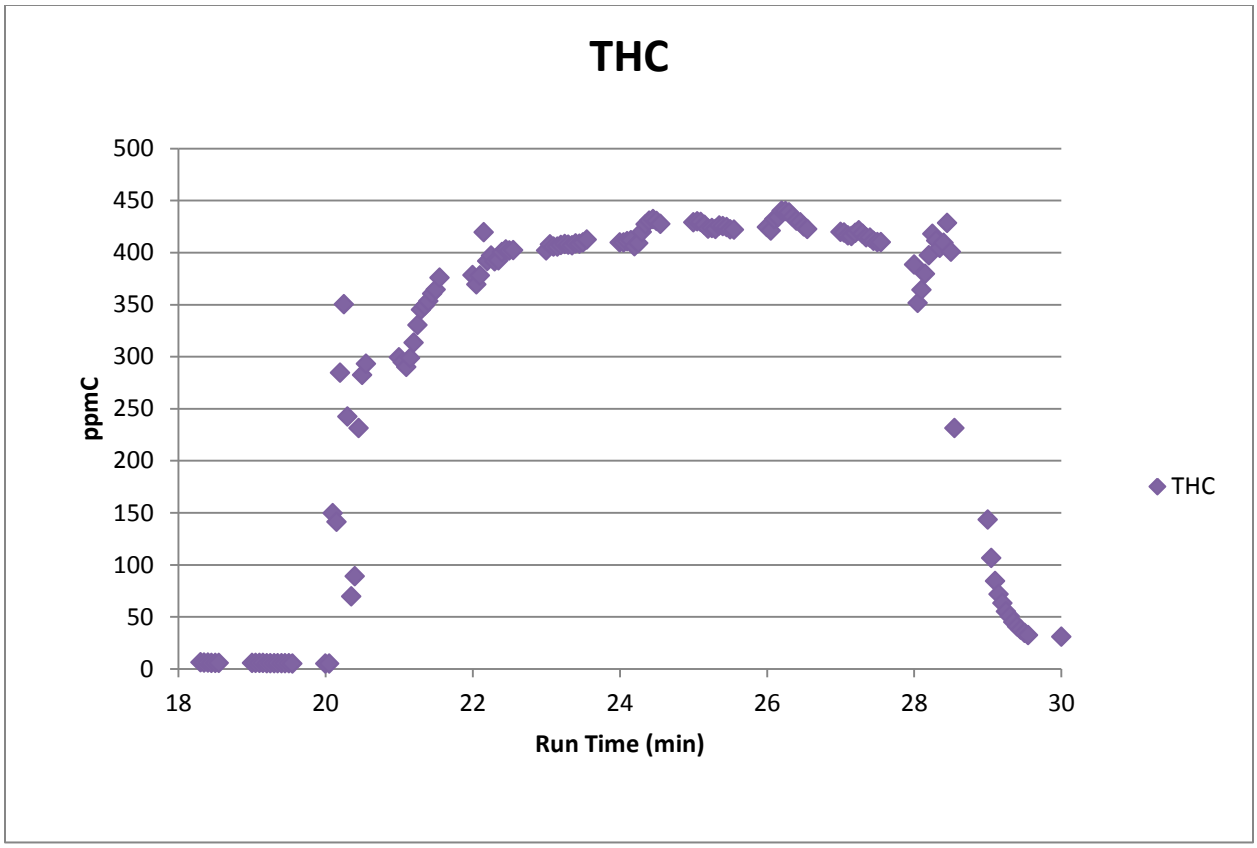
Jet A 6ft 9/13/2011 Olympus HP

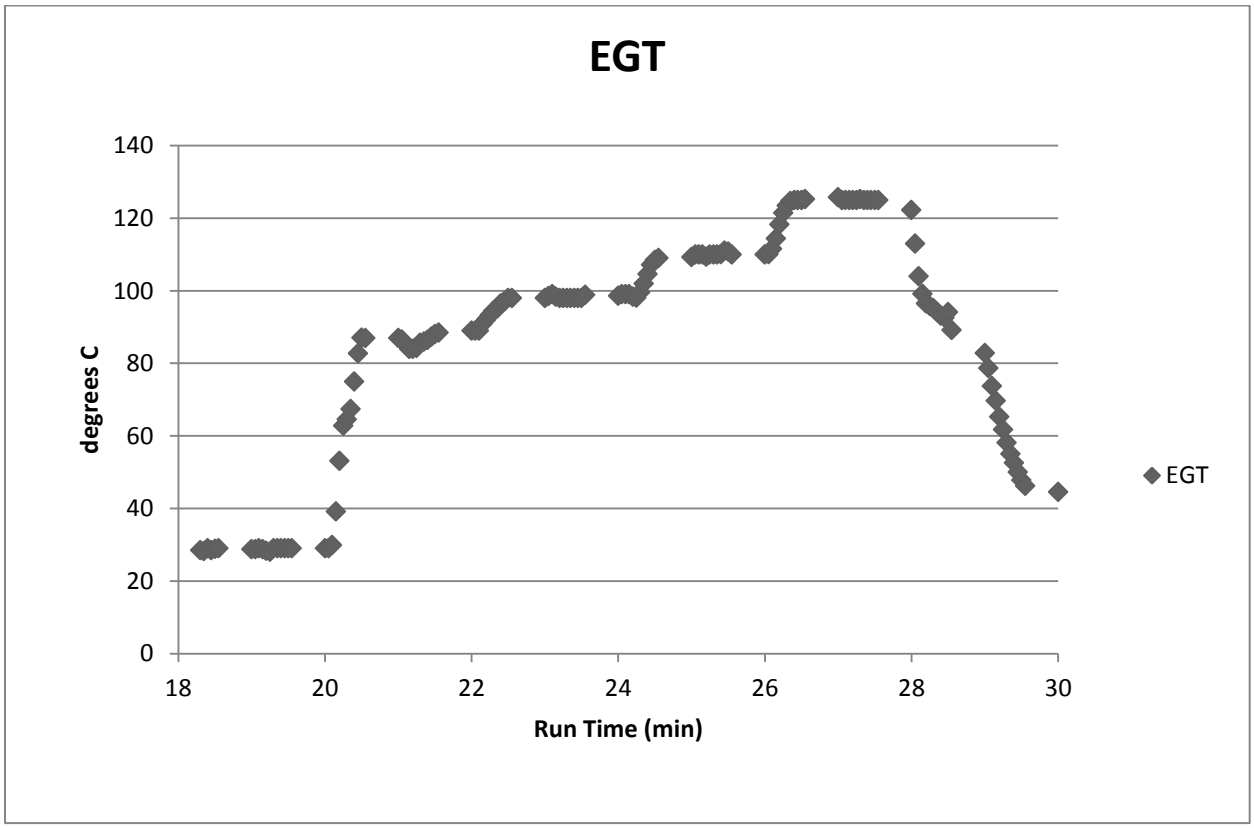




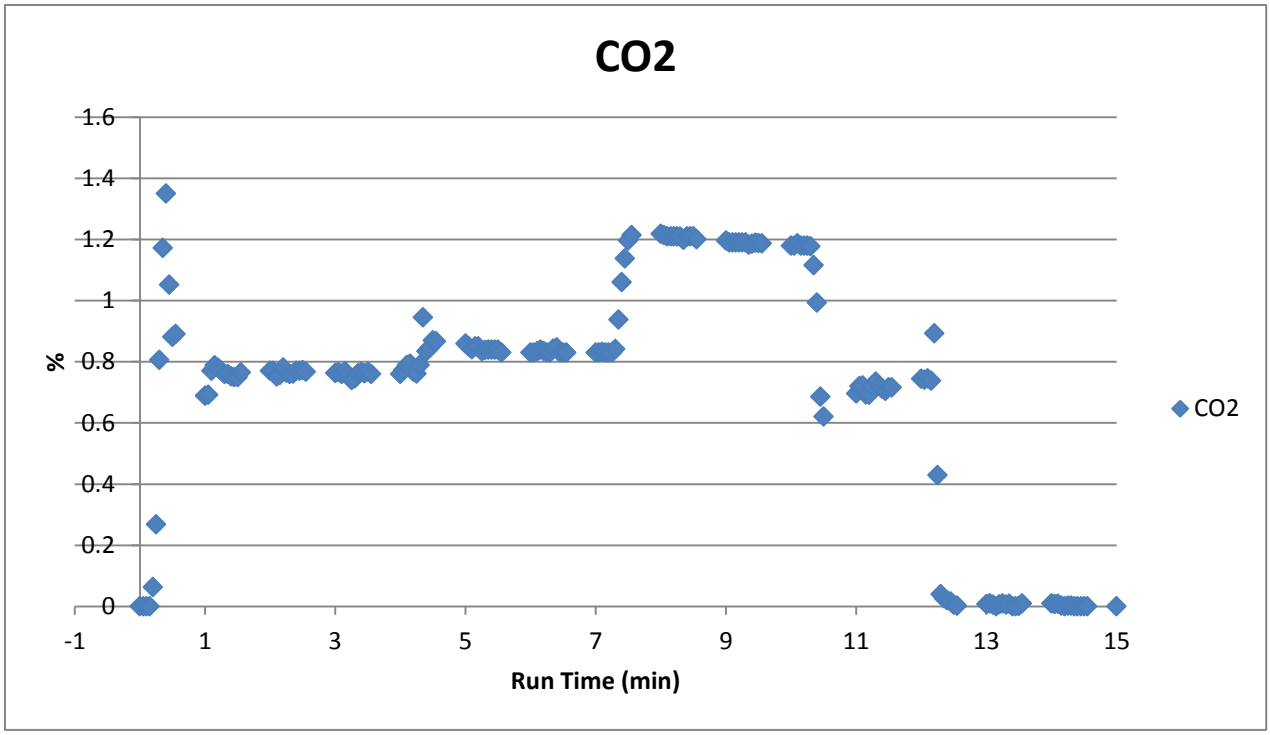

NO
0
-5
-10
-15
-20
-25
18
20
22
24
26
28
30
ppm
Run Time (min)
NO

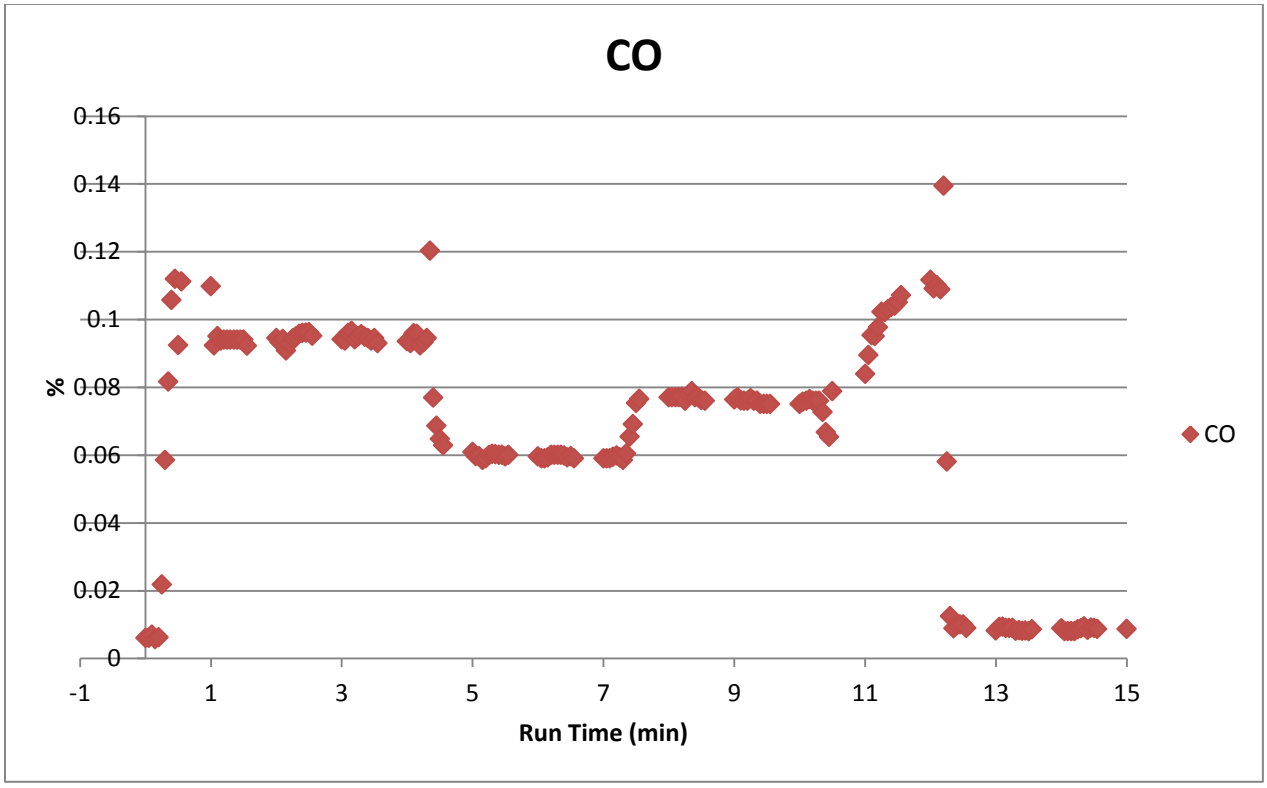

NO2
8
7
6
5
4
3
2
1
0
18
20
22
24
26
28
30
ppm
Run Time (min)
NO2

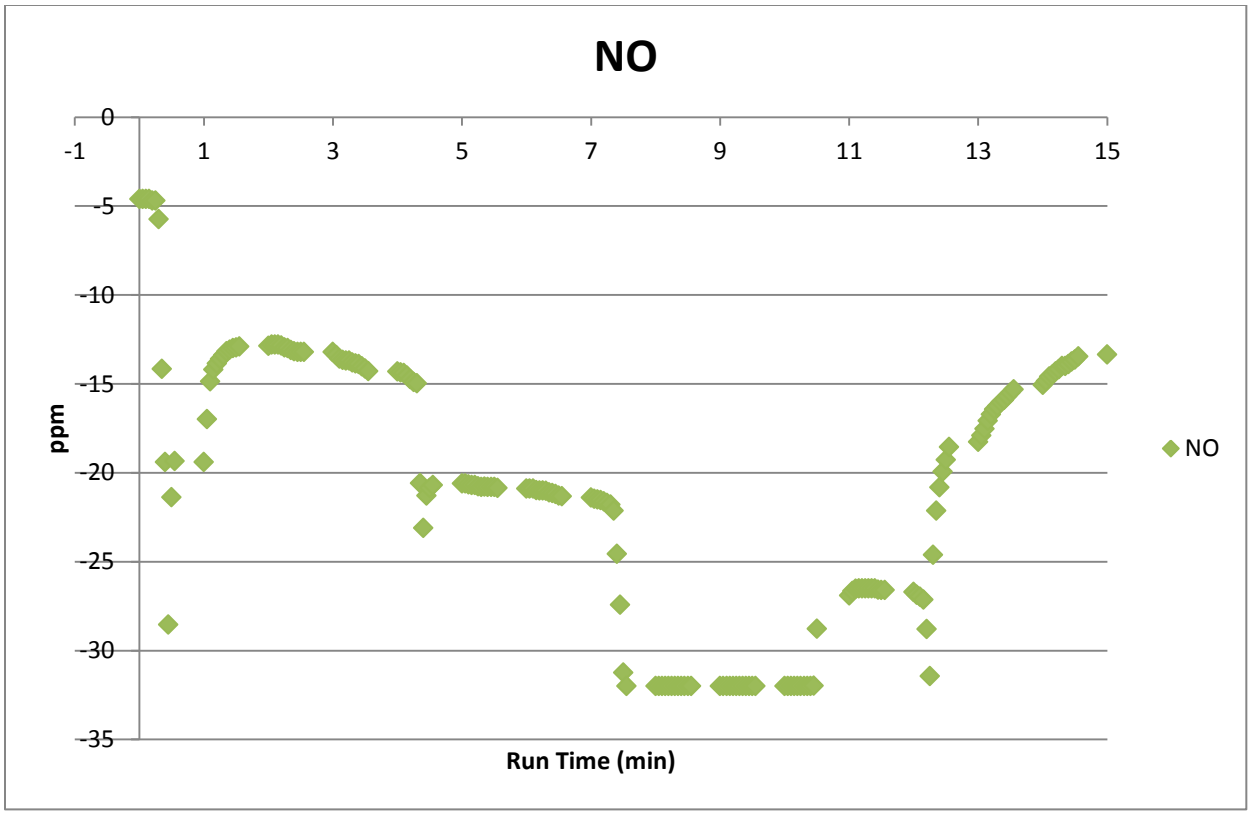

THC
500
450
400
350
300
250
200
150
100
50
0
ppmC
18
20
22
24
26
28
30
Run Time (min)
THC

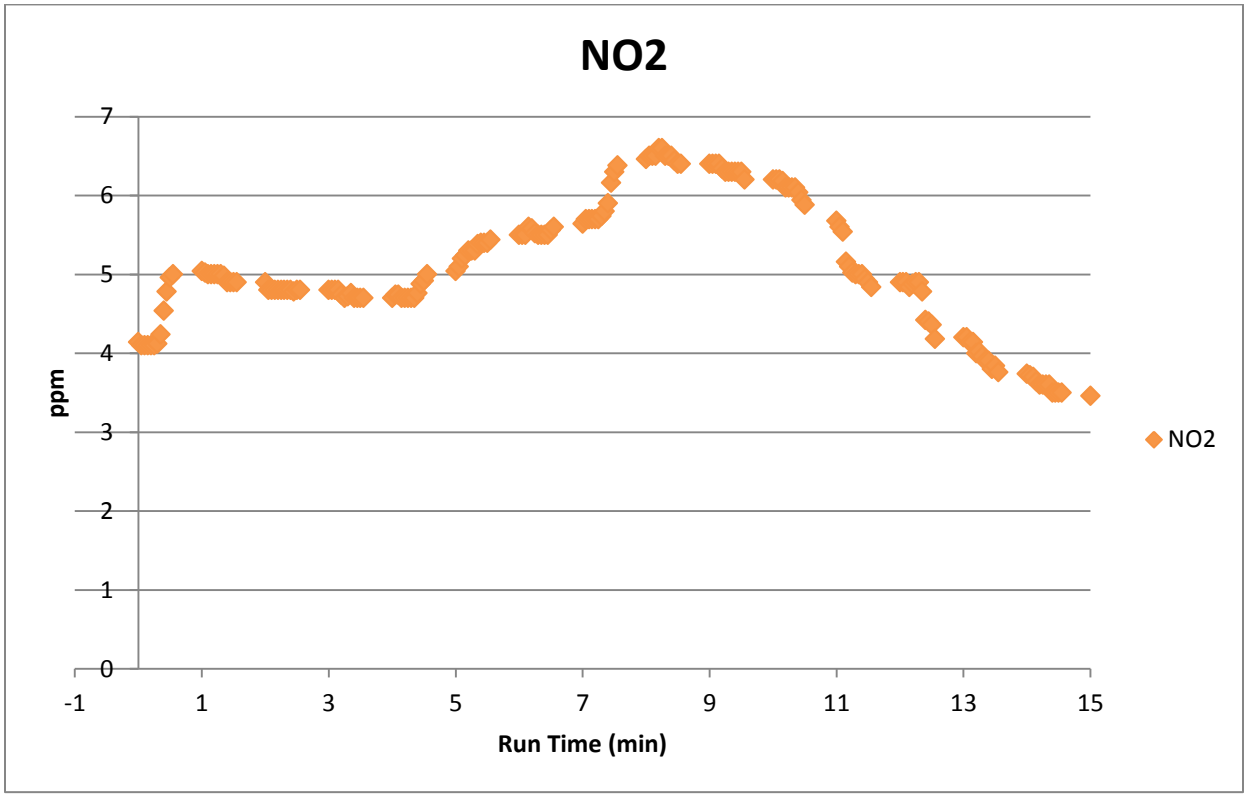

EGT
140
120
100
80
60
40
20
0
degrees C
18
20
22
24
26
28
30
Run Time (min)
EGT

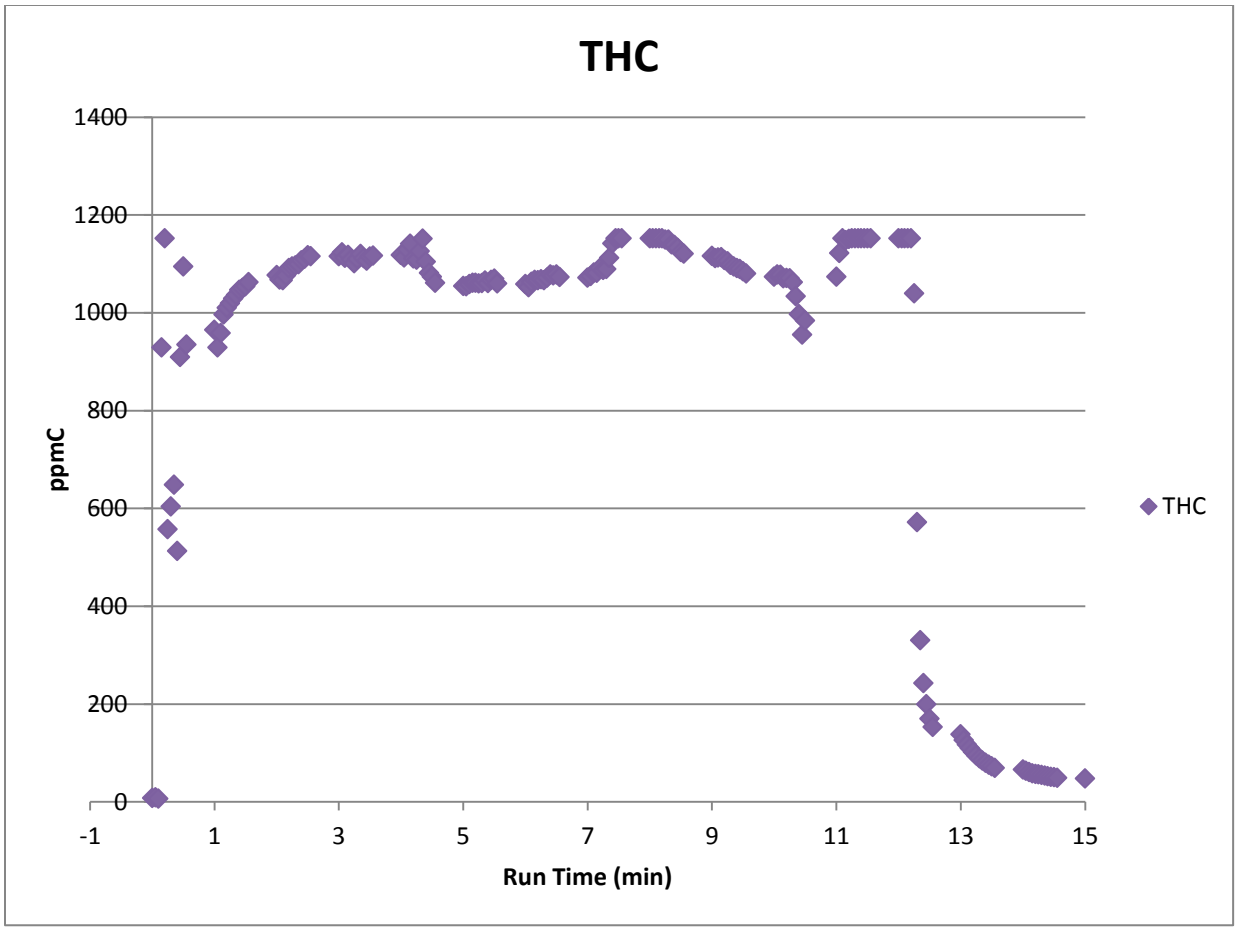
CarbonFilter1 NCF 3/27/2012 Olympus HP



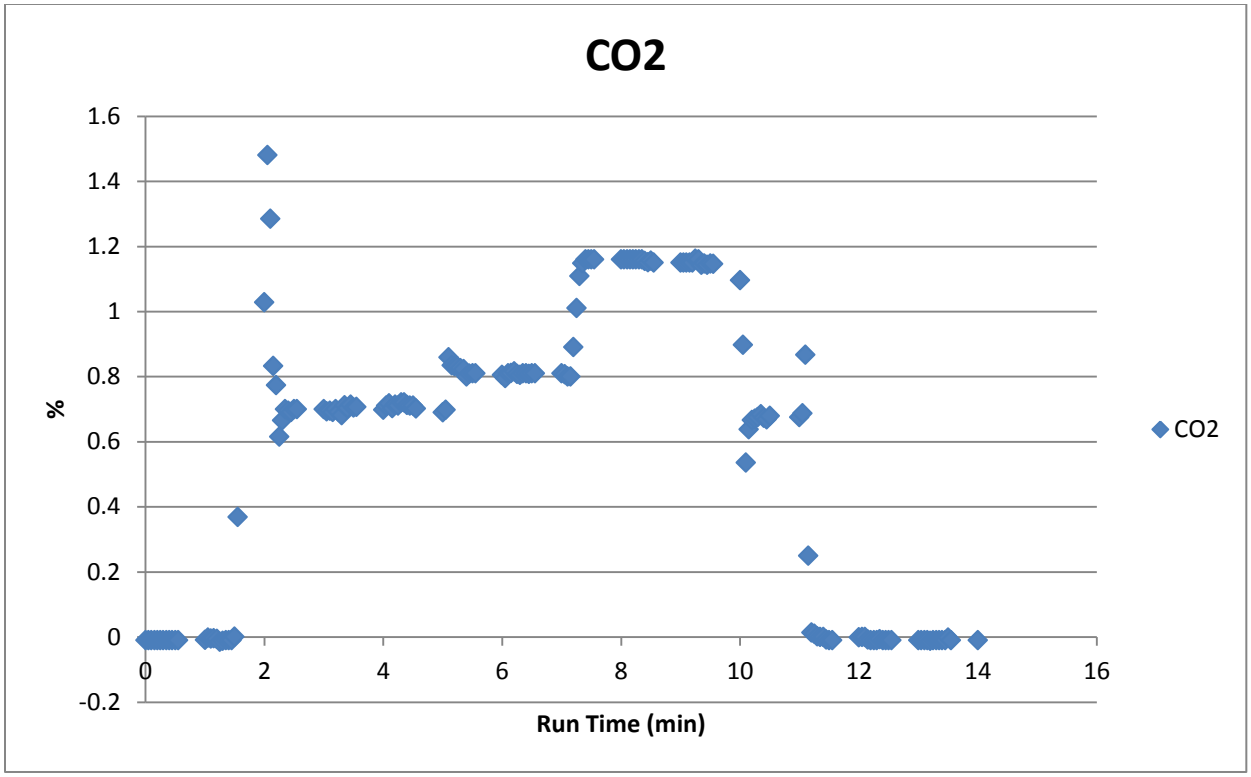


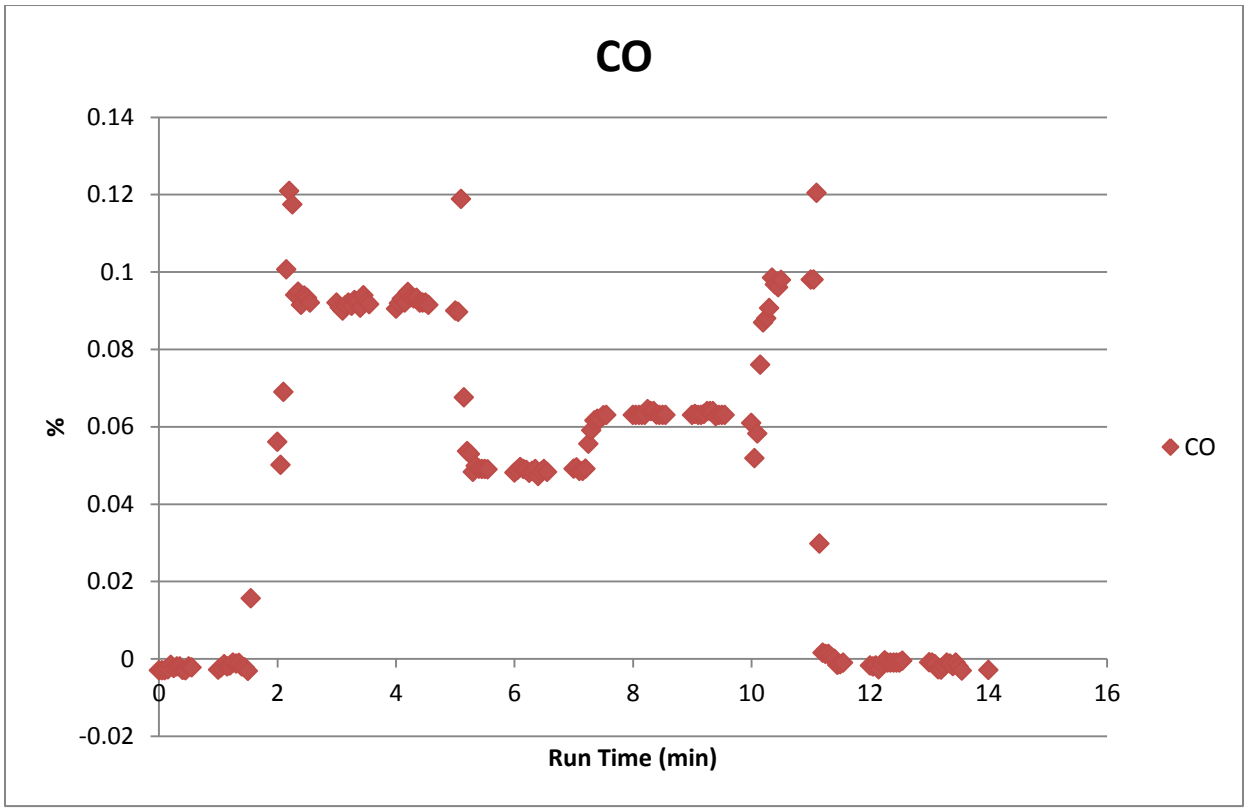

NO
0
-5
-10
-15
-20
-25
-30
-35
-1
1
3
5
7
9
11
13
15
ppm
Run Time (min)
NO

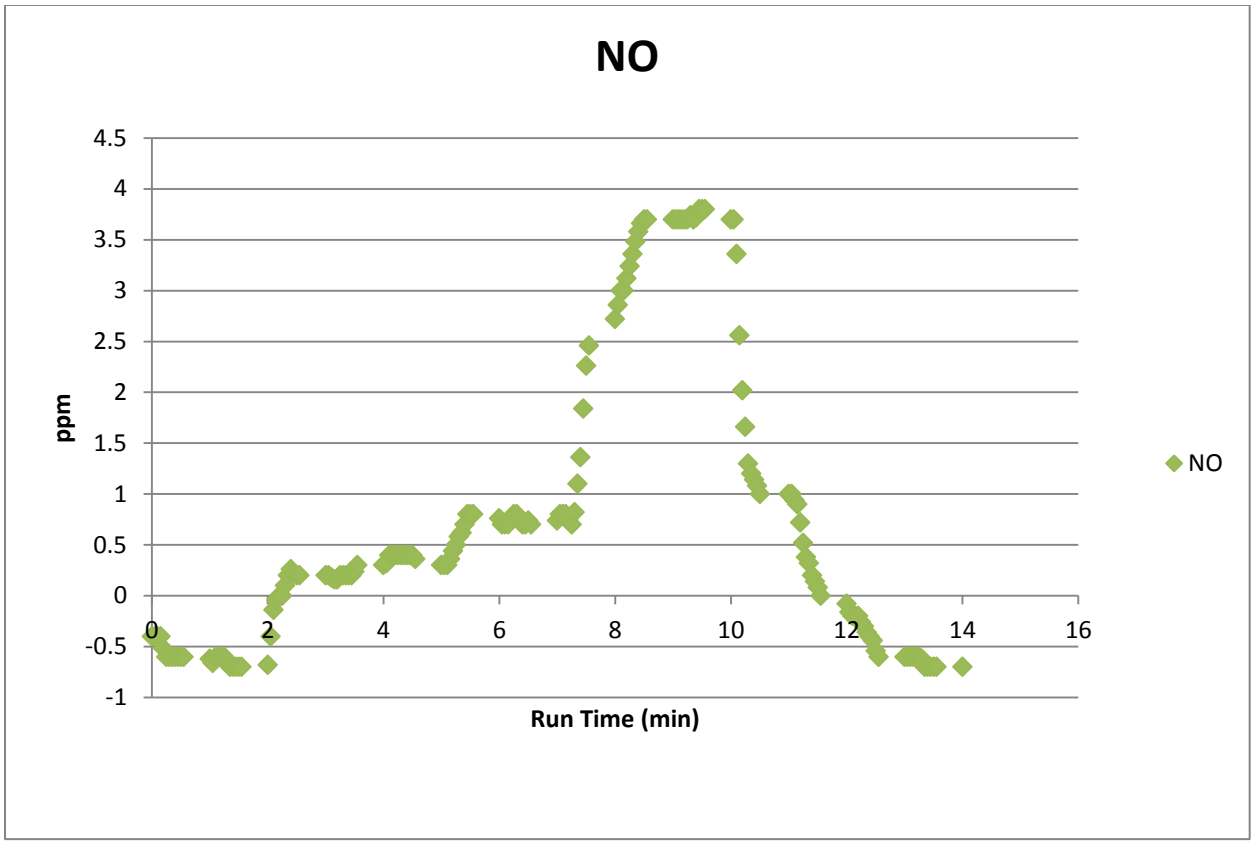

NO2
7
6
5
4
3
2
1
0
-1
1
3
5
7
9
11
13
15
ppm
Run Time (min)
NO2

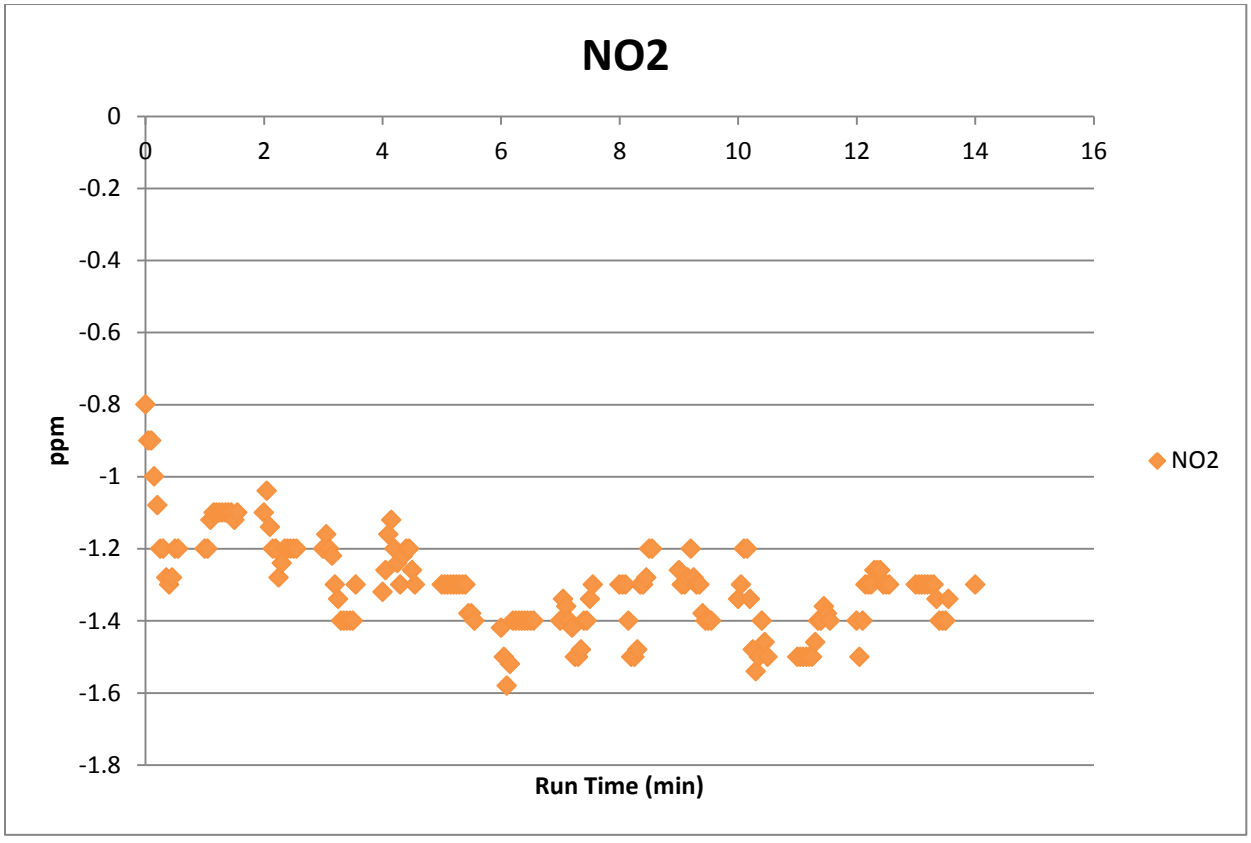

THC
1400
1200
1000
800
600
400
200
0
ppmC
-1
1
3
5
7
9
11
13
15
Run Time (min)
THC

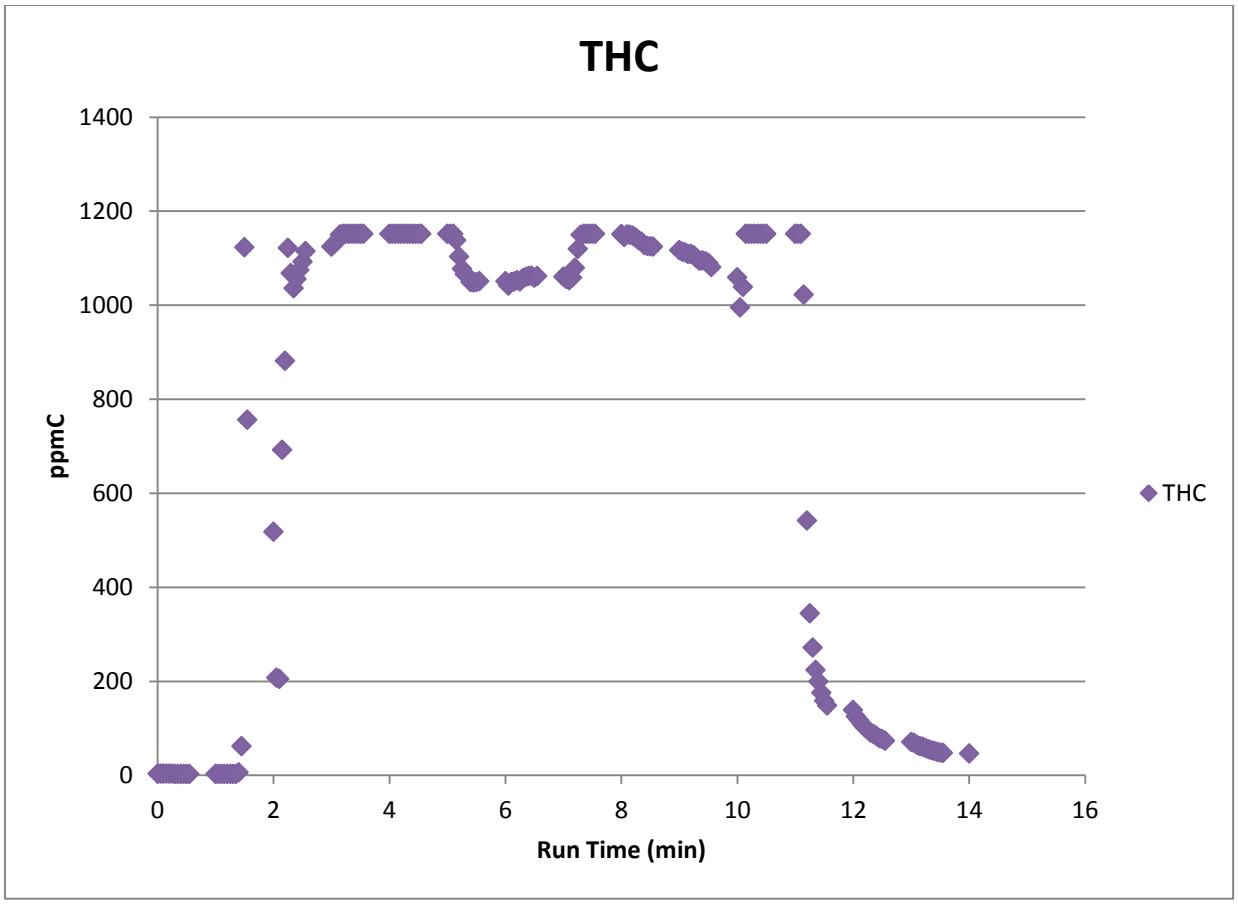
CarbonFilter1 CF 3/27/2012 Olympus HP



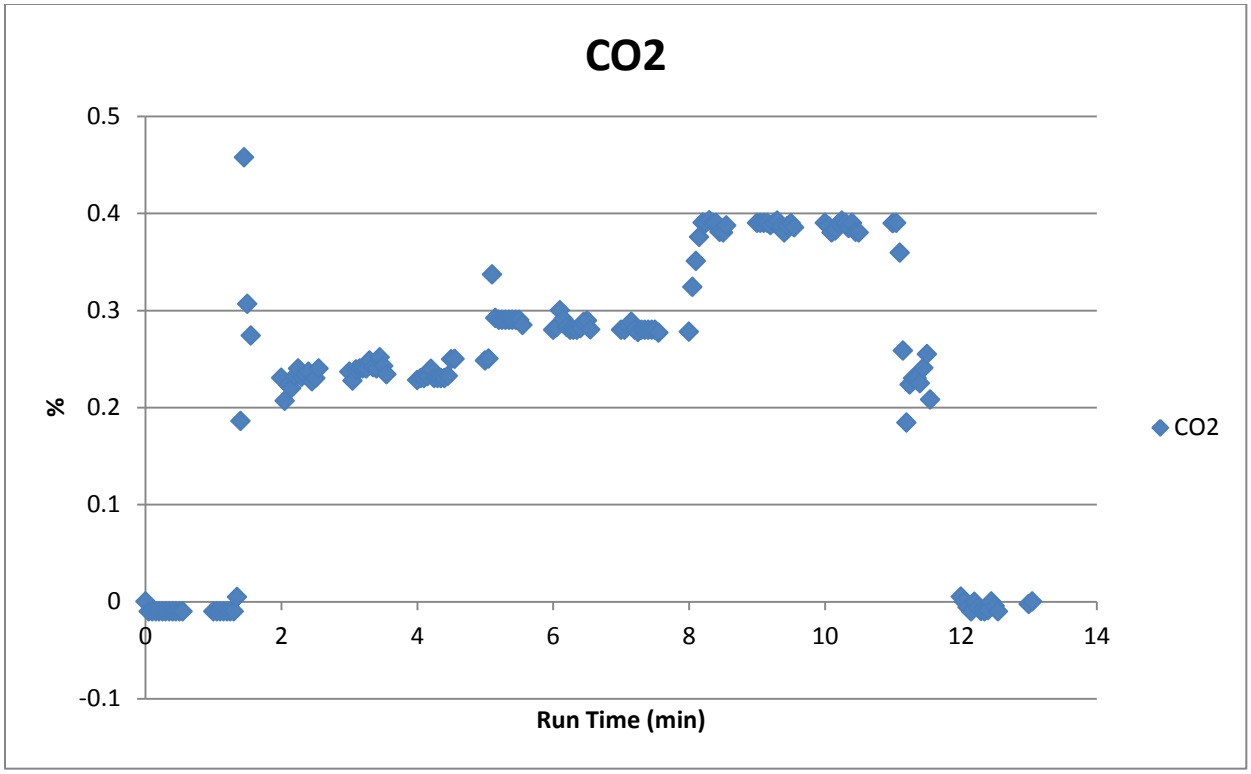


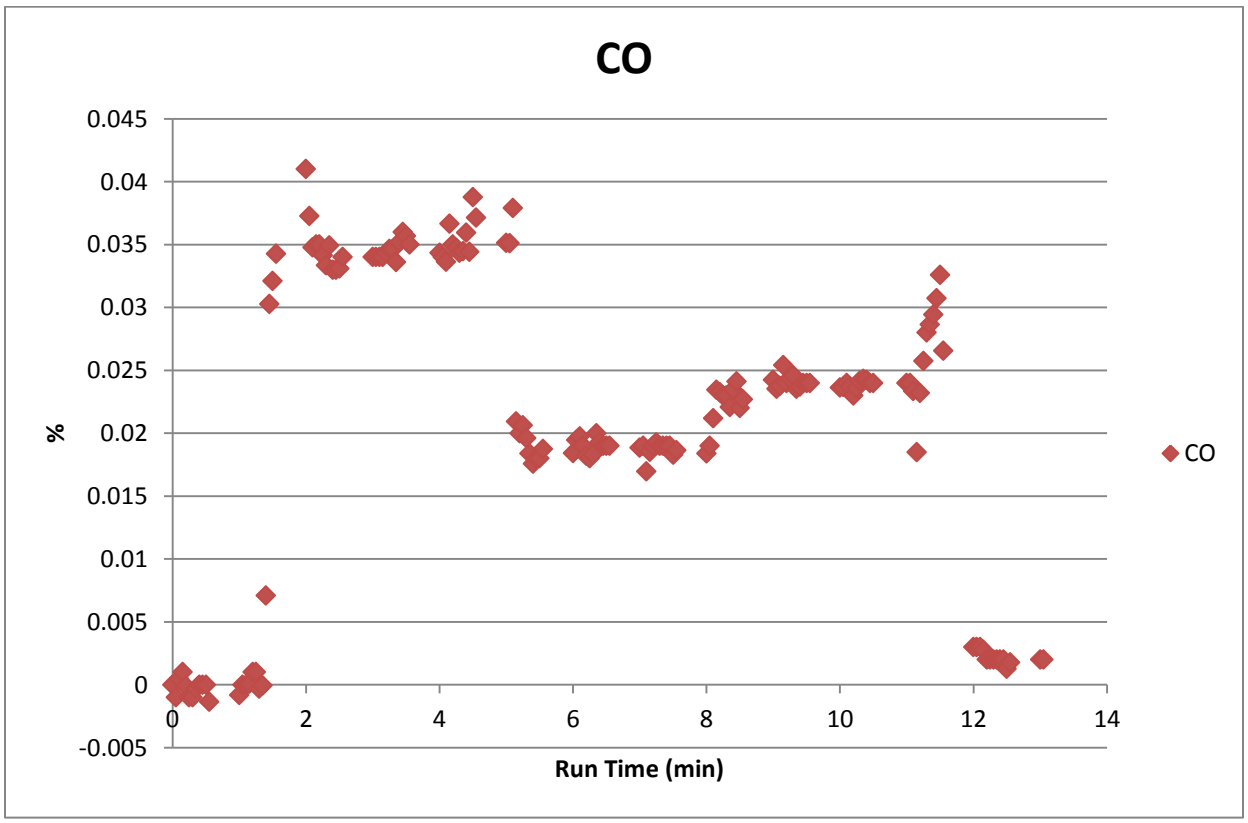

NO
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
ppm
0
2
4
6
8
10
12
14
16
Run Time (min)
NO

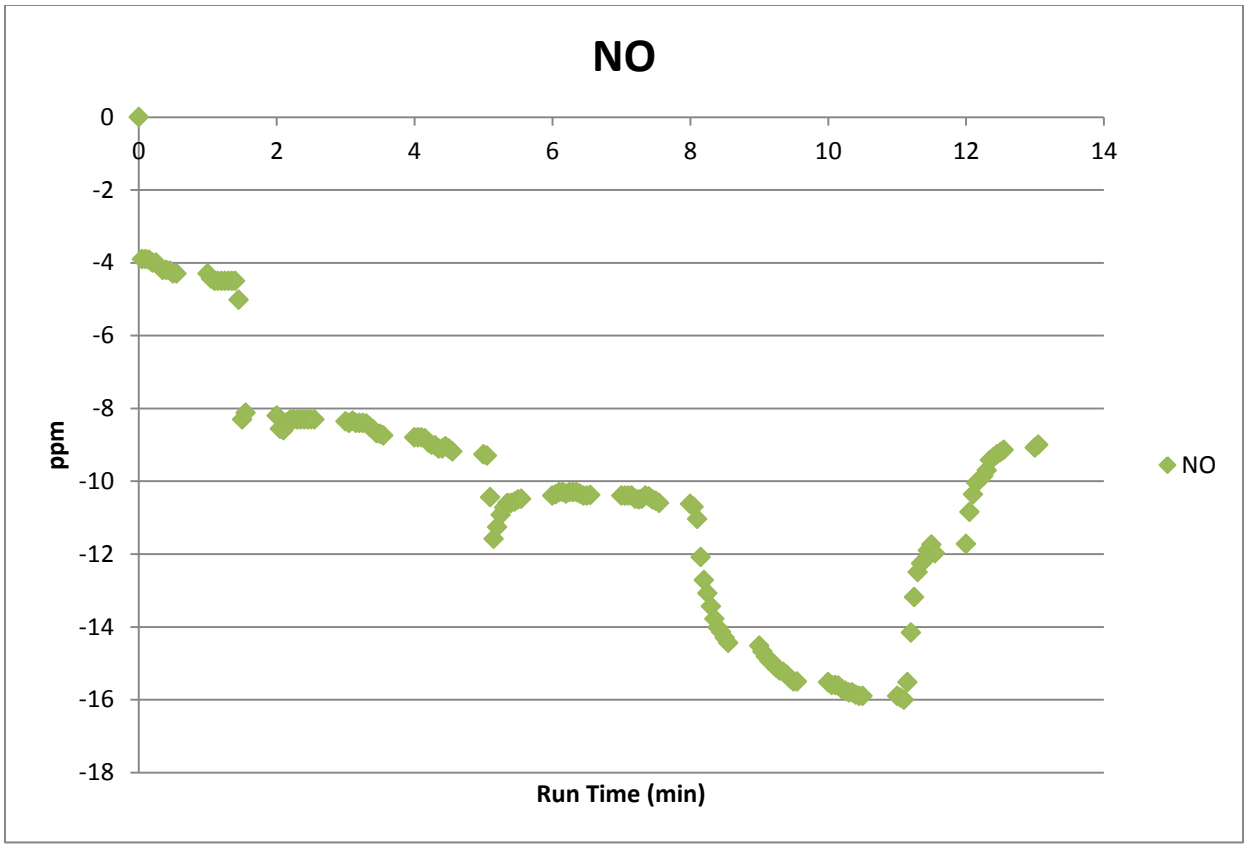

NO2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
ppm
0
2
4
6
8
10
12
14
16
Run Time (min)
NO2

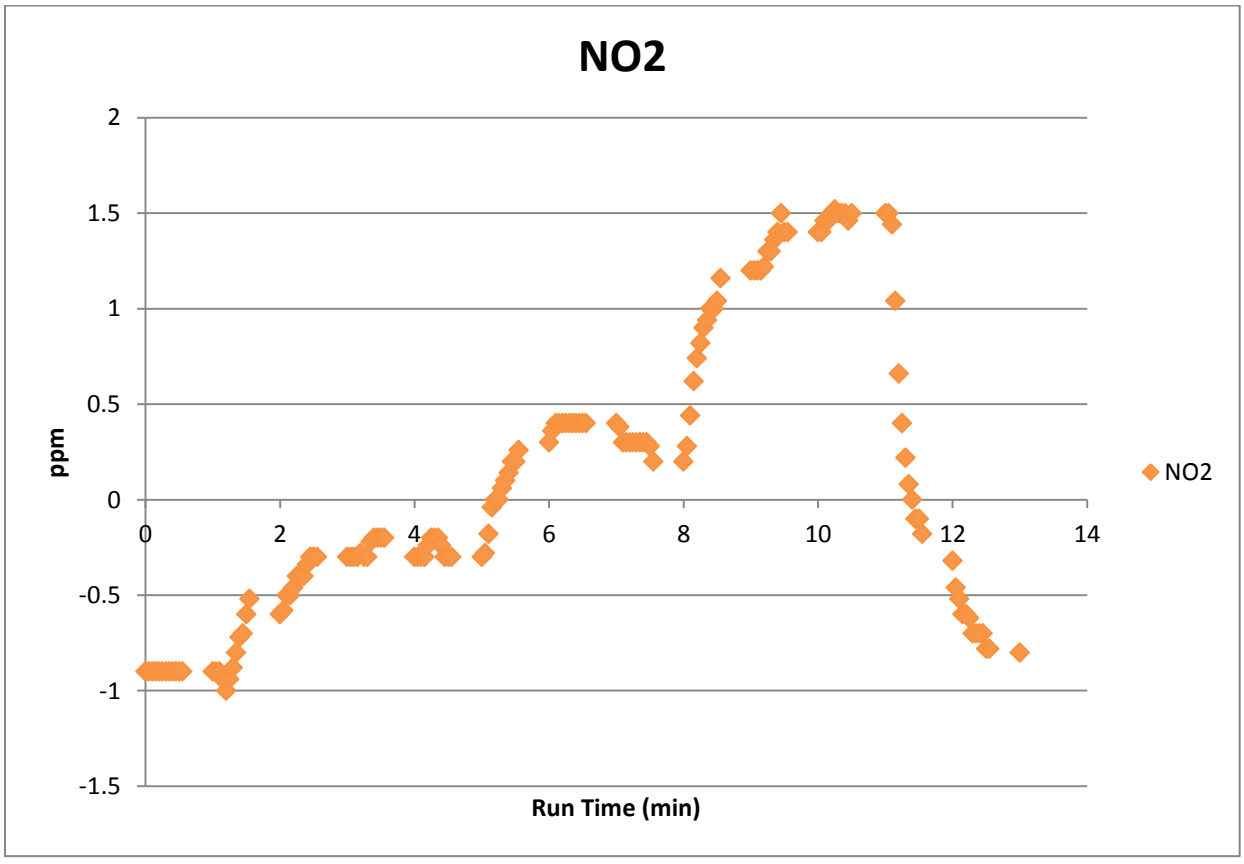

THC
1400
1200
1000
800
600
400
200
0
ppmC
0
2
4
6
8
10
12
14
16
Run Time (min)
THC

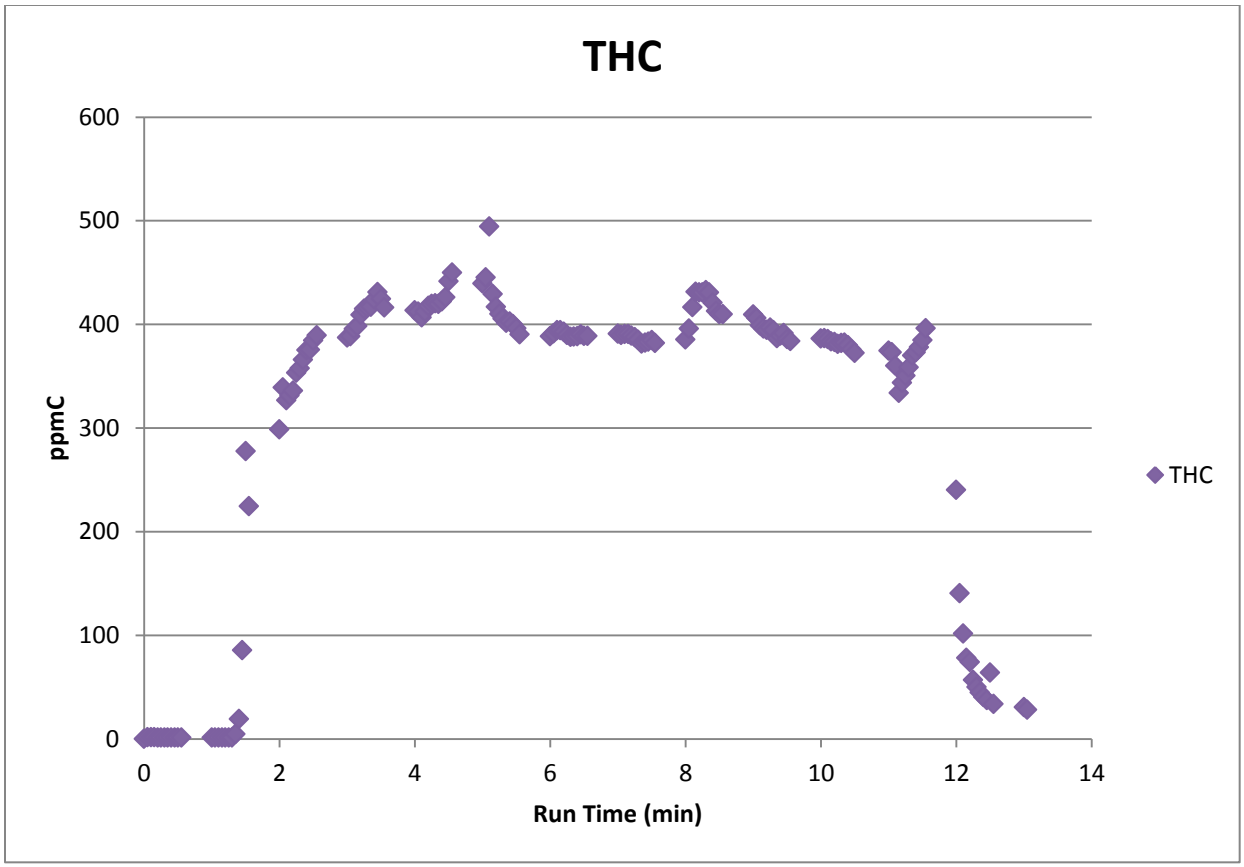
CarbonFilter2 NCF 4/23/2012 Olympus HP



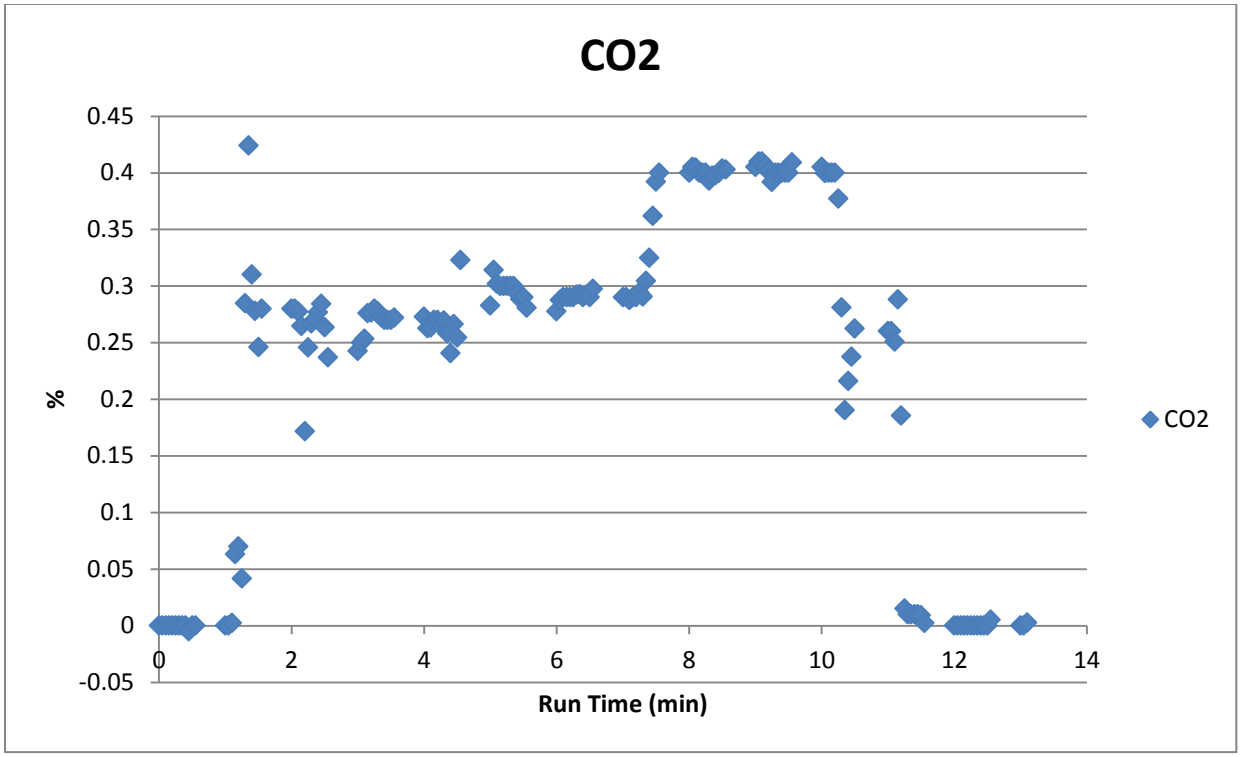


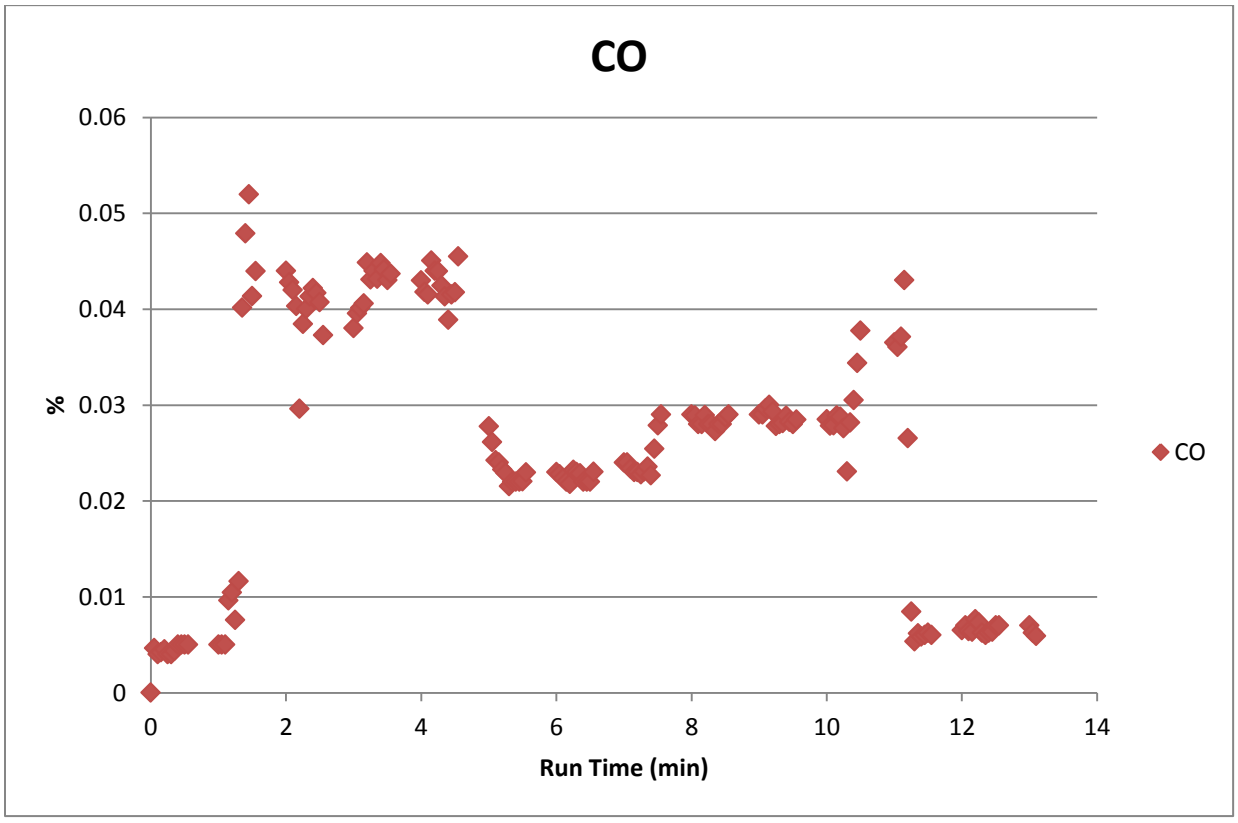

NO
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
ppm
0
2
4
6
8
10
12
14
Run Time (min)
NO

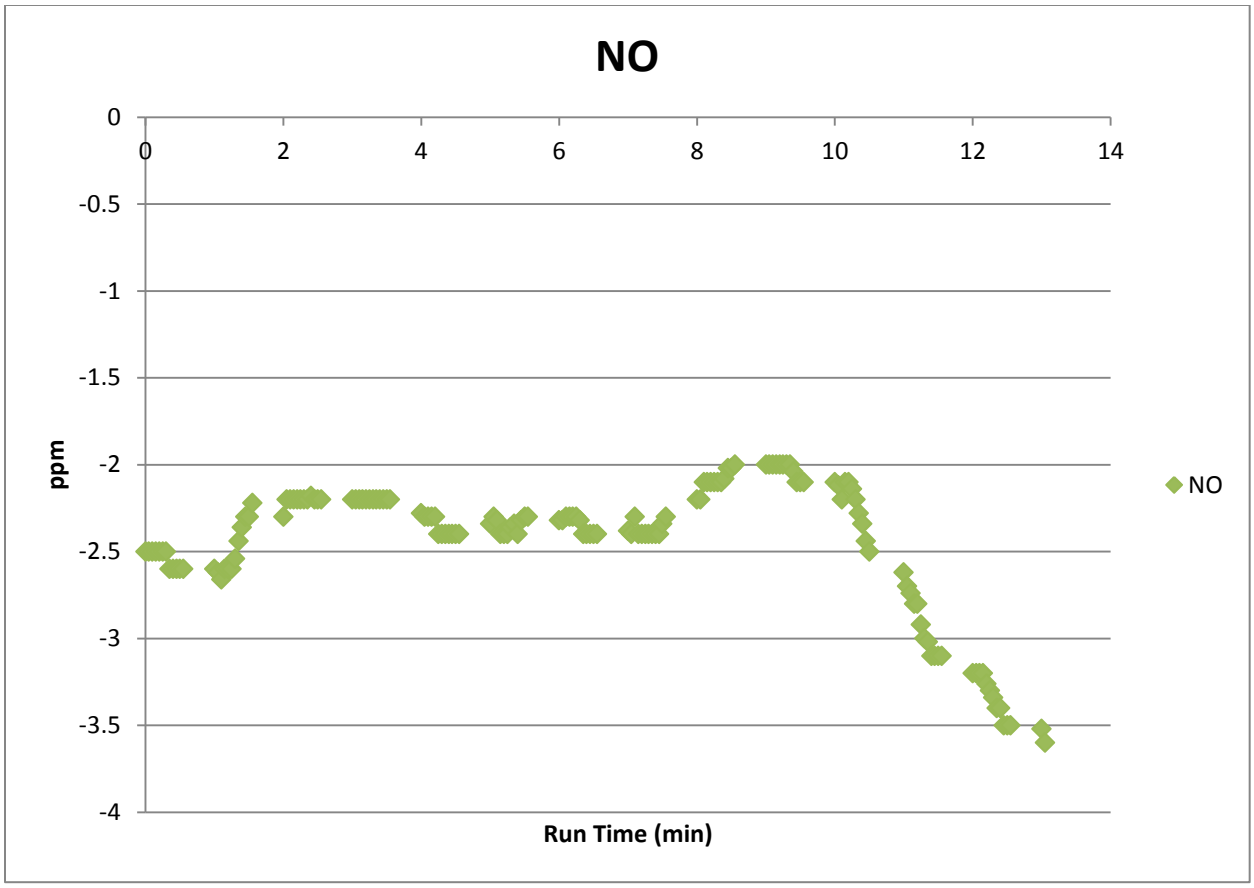

NO2
2
1.5
1
0.5
0
-0.5
-1
-1.5
ppm
0
2
4
6
8
10
12
14
Run Time (min)
NO2

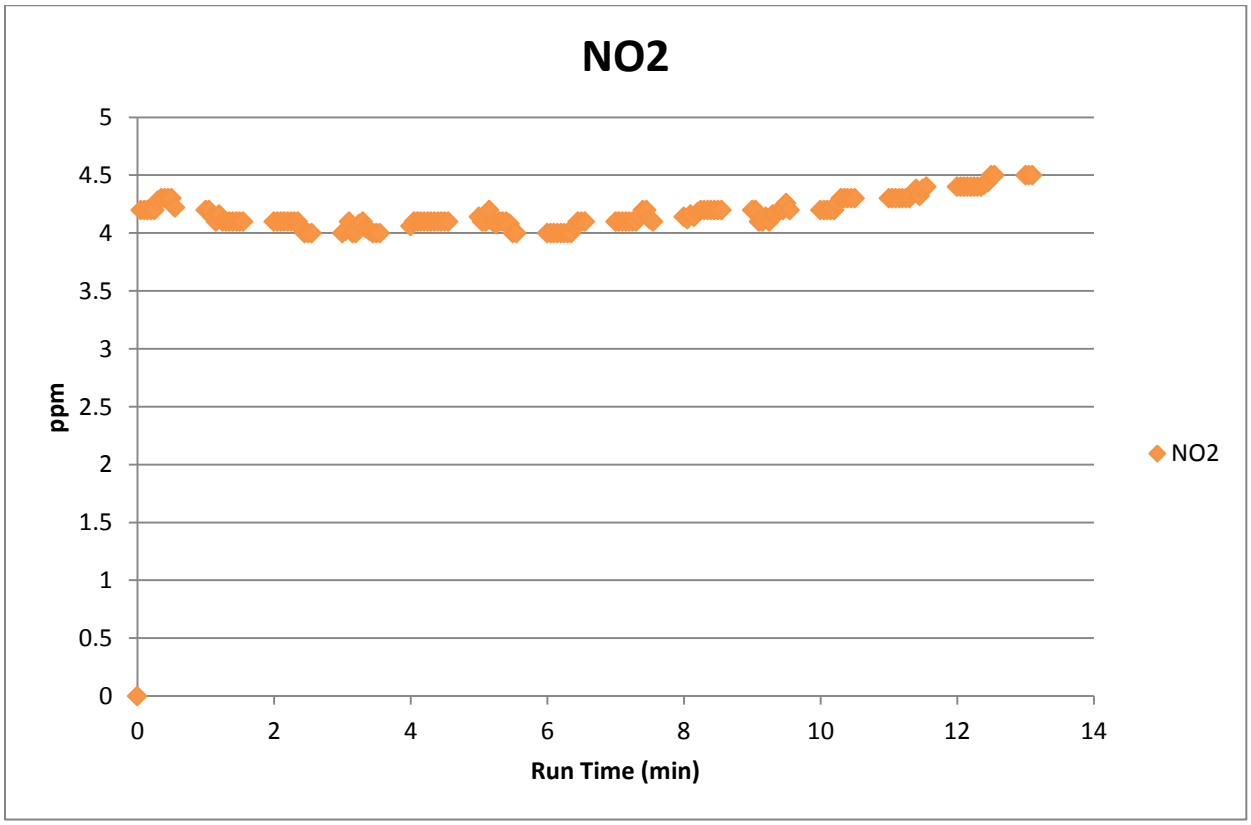

THC
600
500
400
300
200
100
0
ppmC
0
2
4
6
8
10
12
14
Run Time (min)
THC

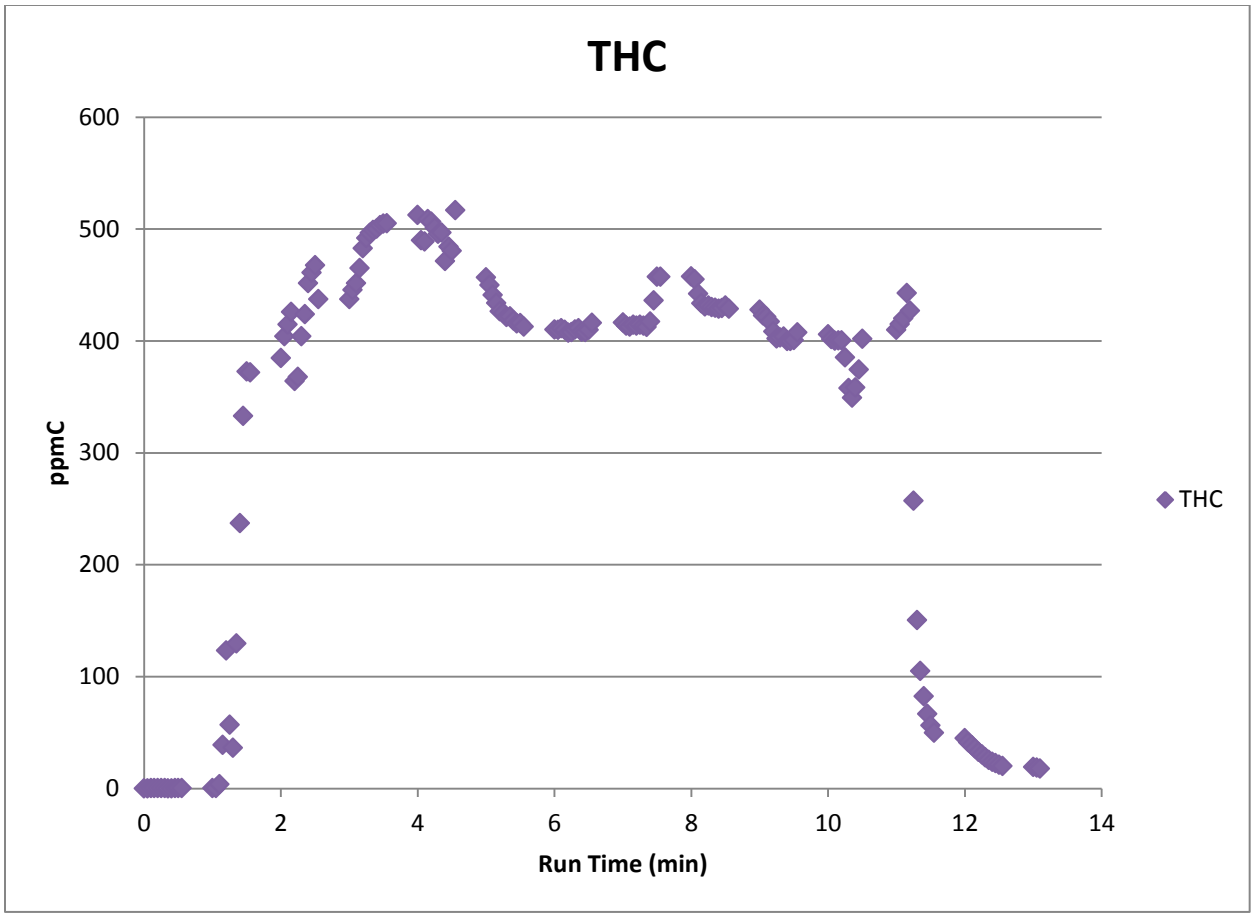
CarbonFilter2 CF 4/23/2012 Olympus HP





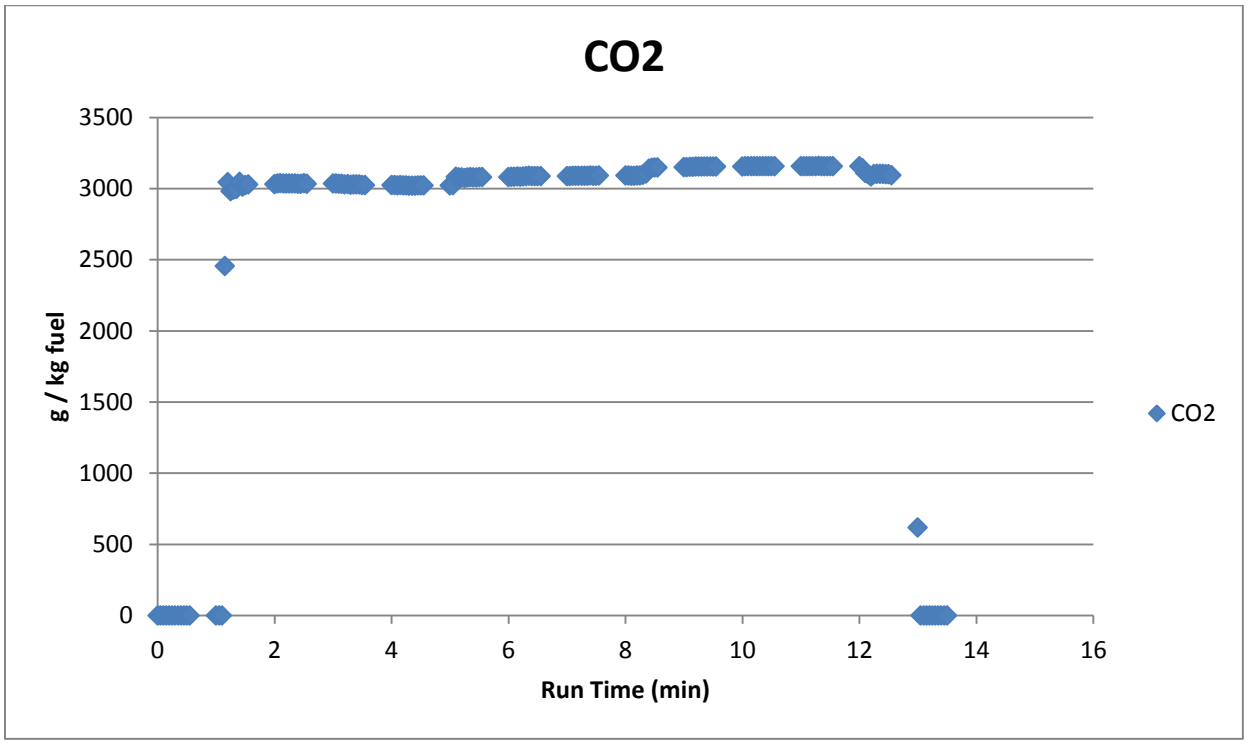

NO
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
0
2
4
6
8
10
12
14
ppm
Run Time (min)
NO

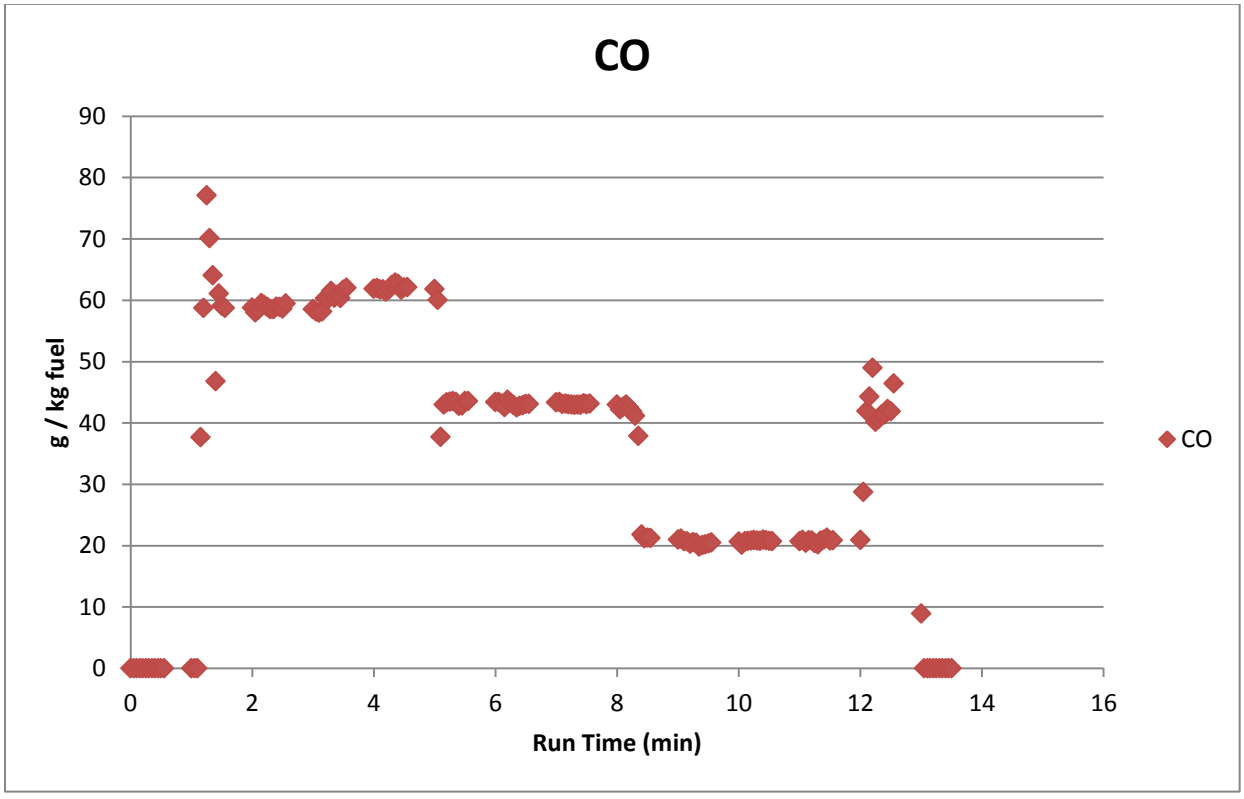

NO2
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
2
4
6
8
10
12
14
ppm
Run Time (min)
NO2

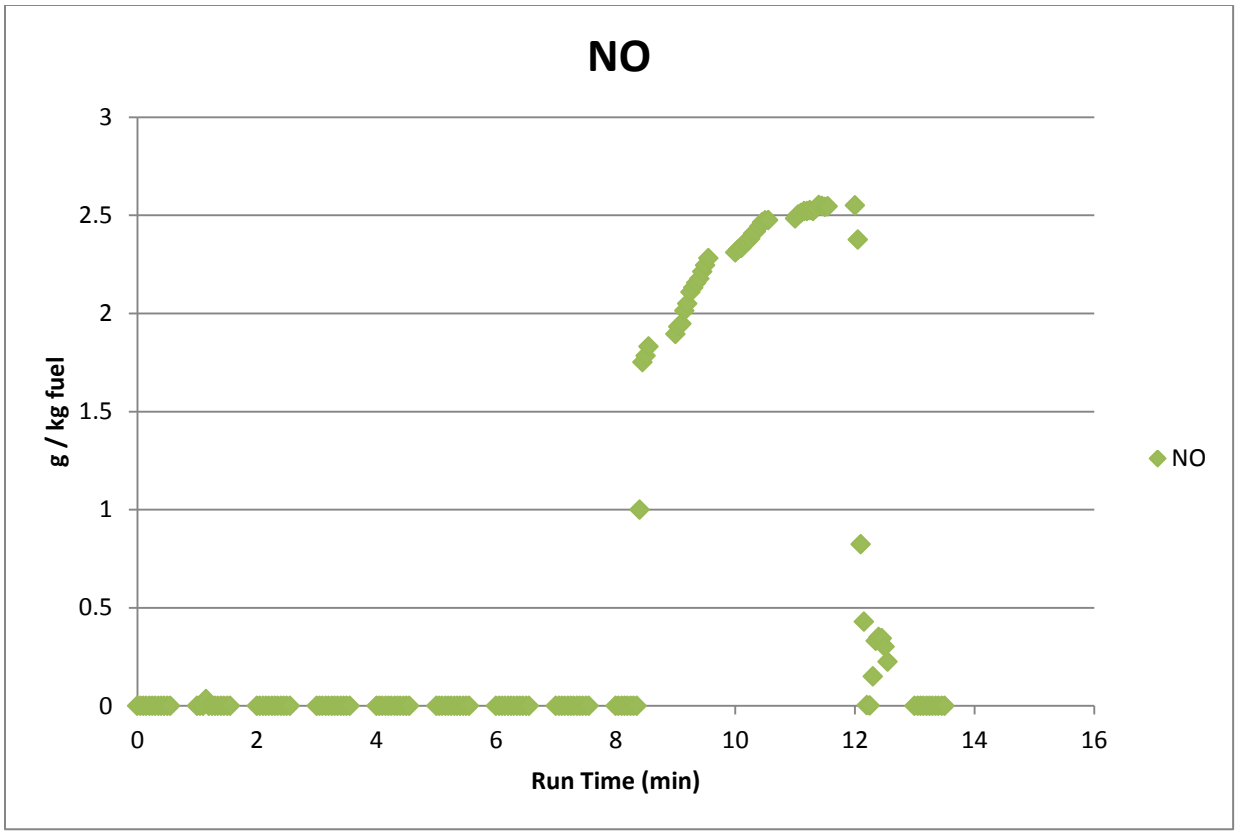

THC
600
500
400
300
200
100
0
ppmC
0
2
4
6
8
10
12
14
Run Time (min)
THC

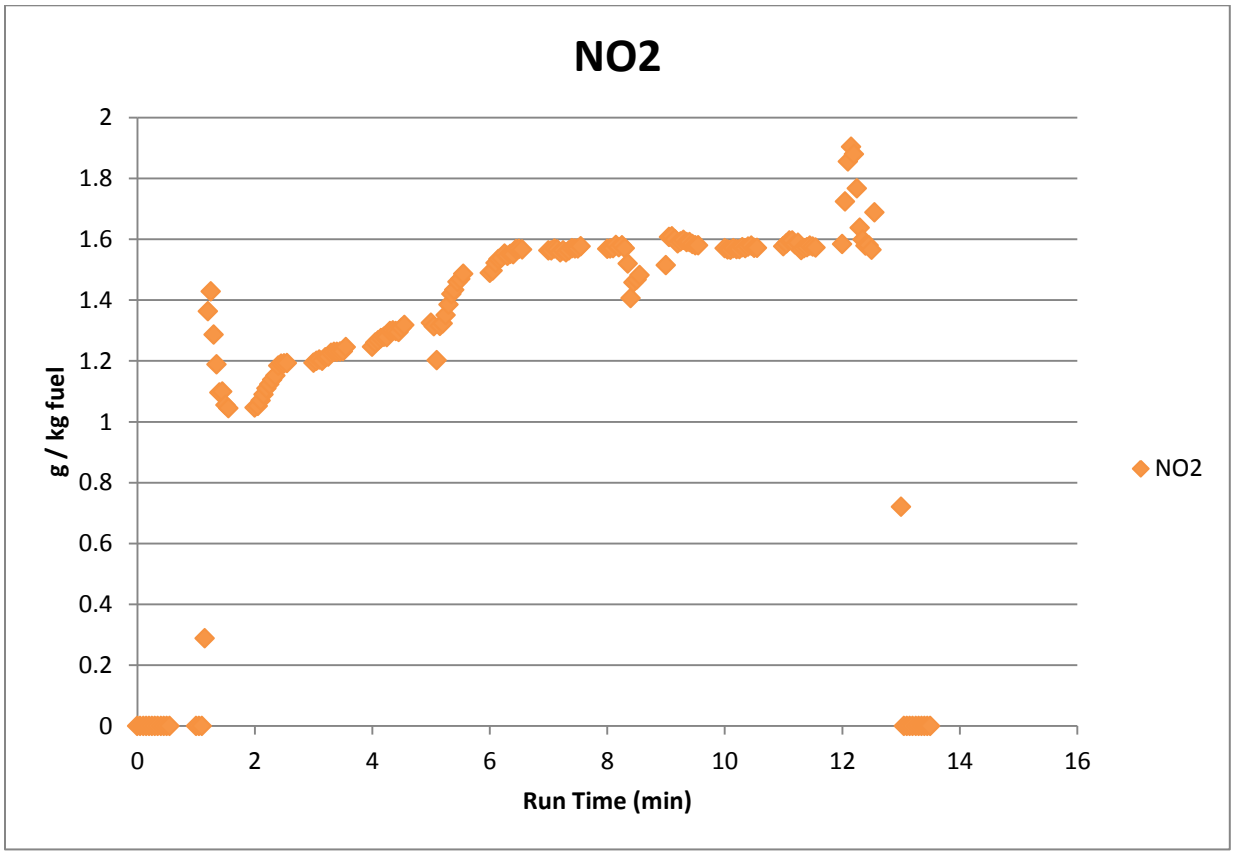
Appendix B: Results from 11/29/2012 Salina Sampling

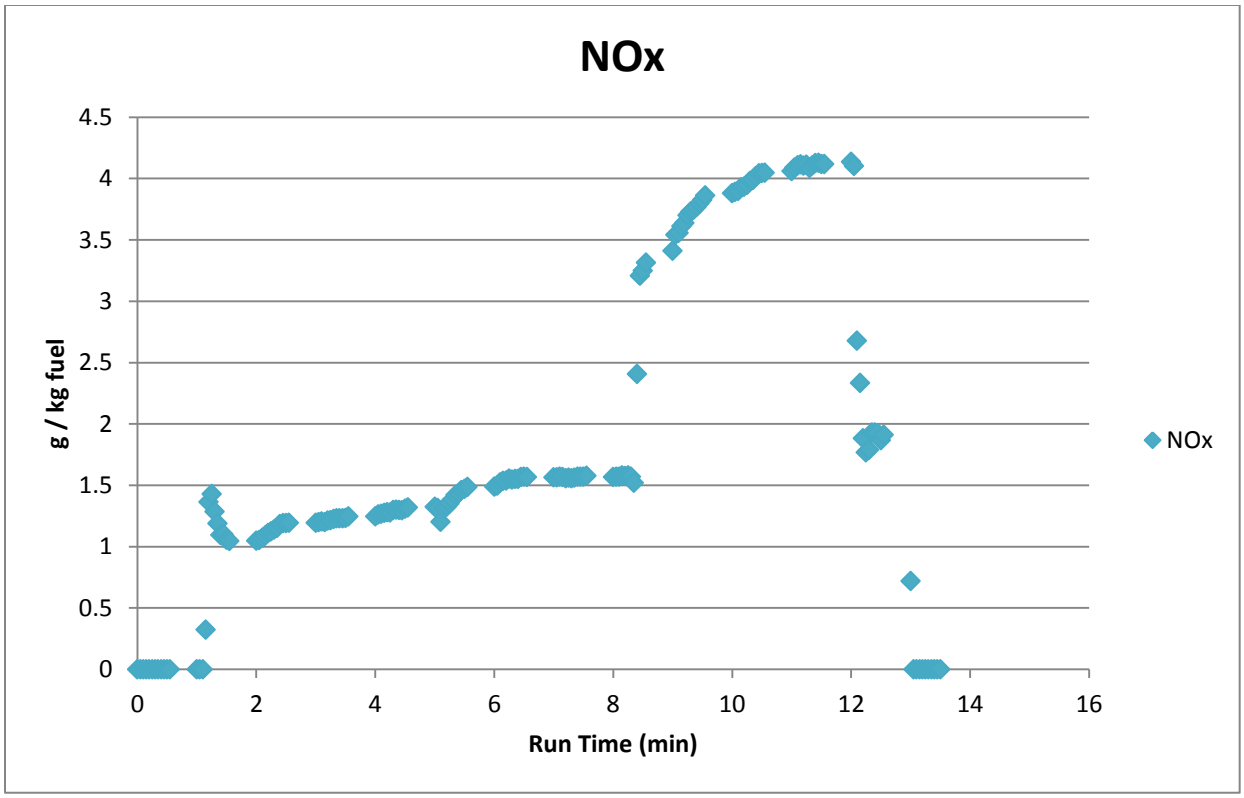
JetA 11/29/2011 PT6

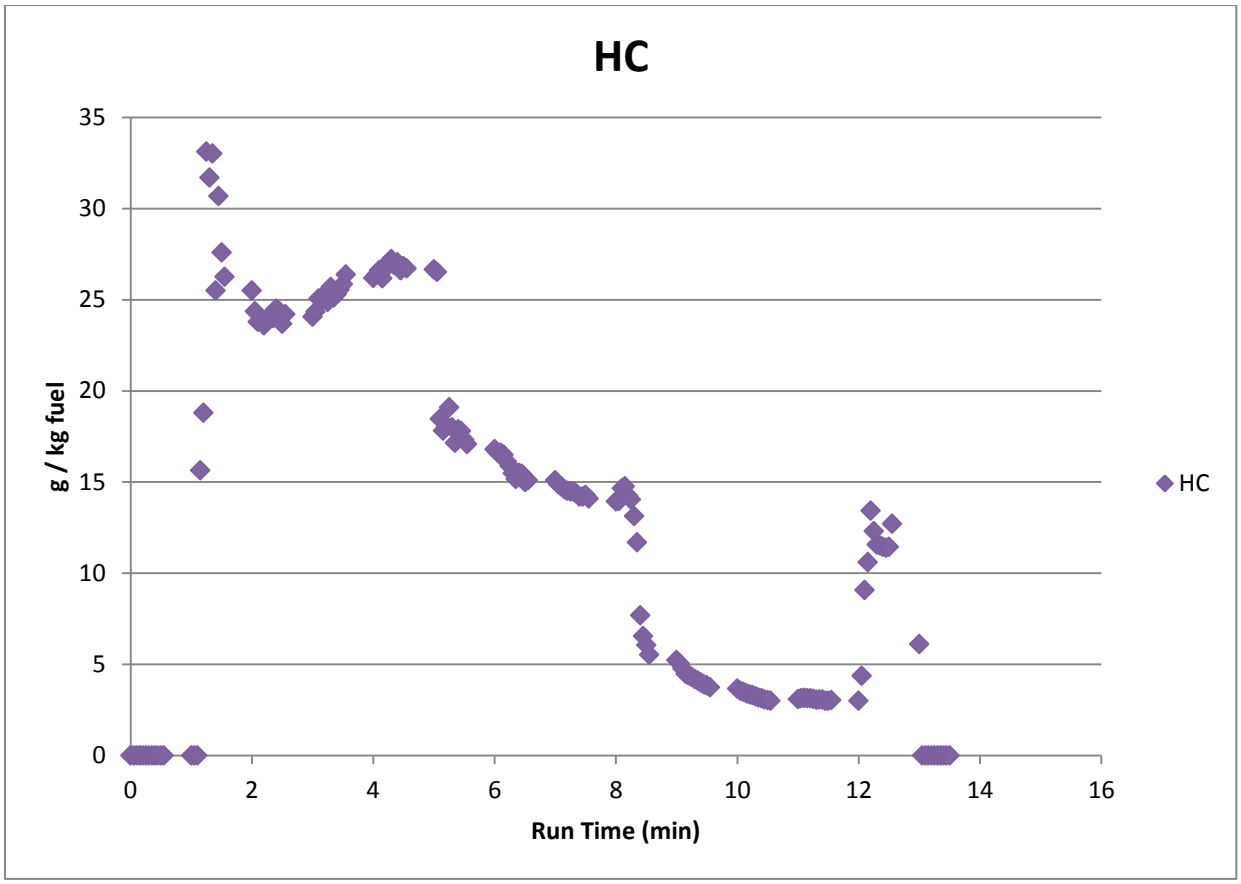


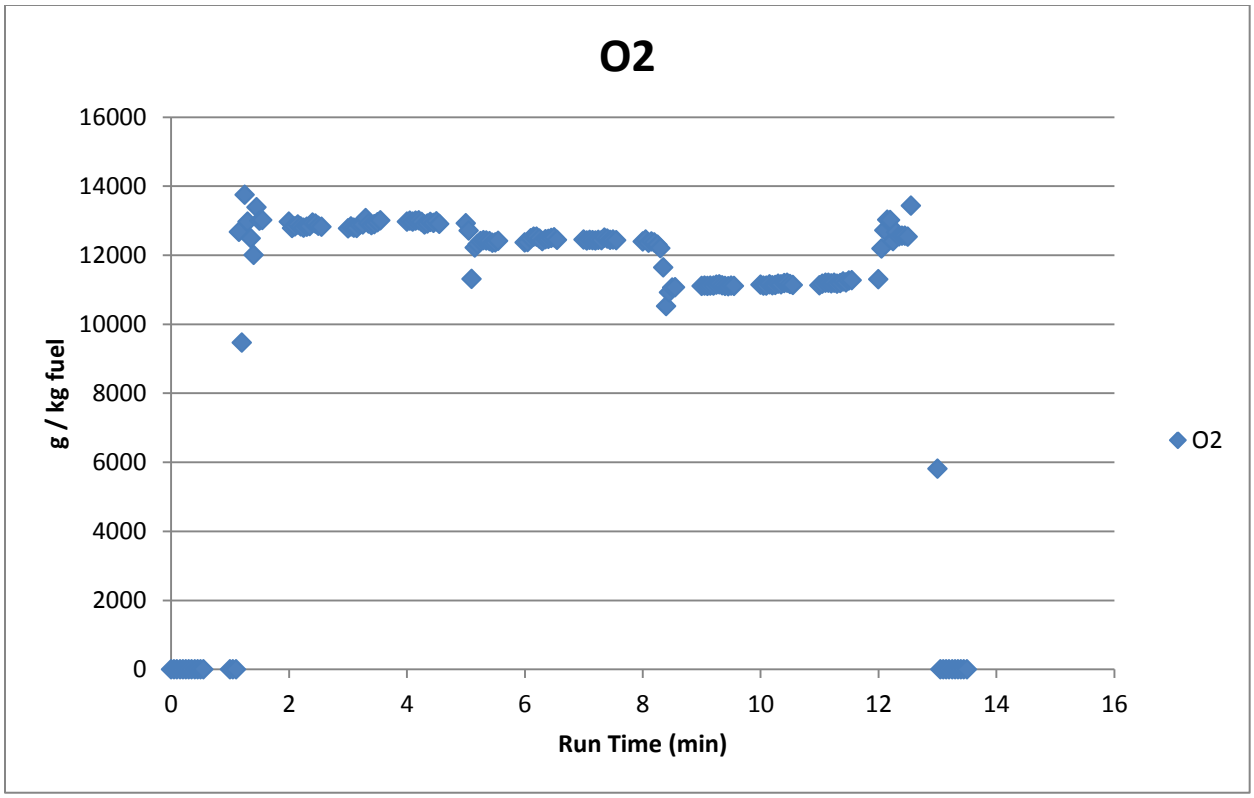


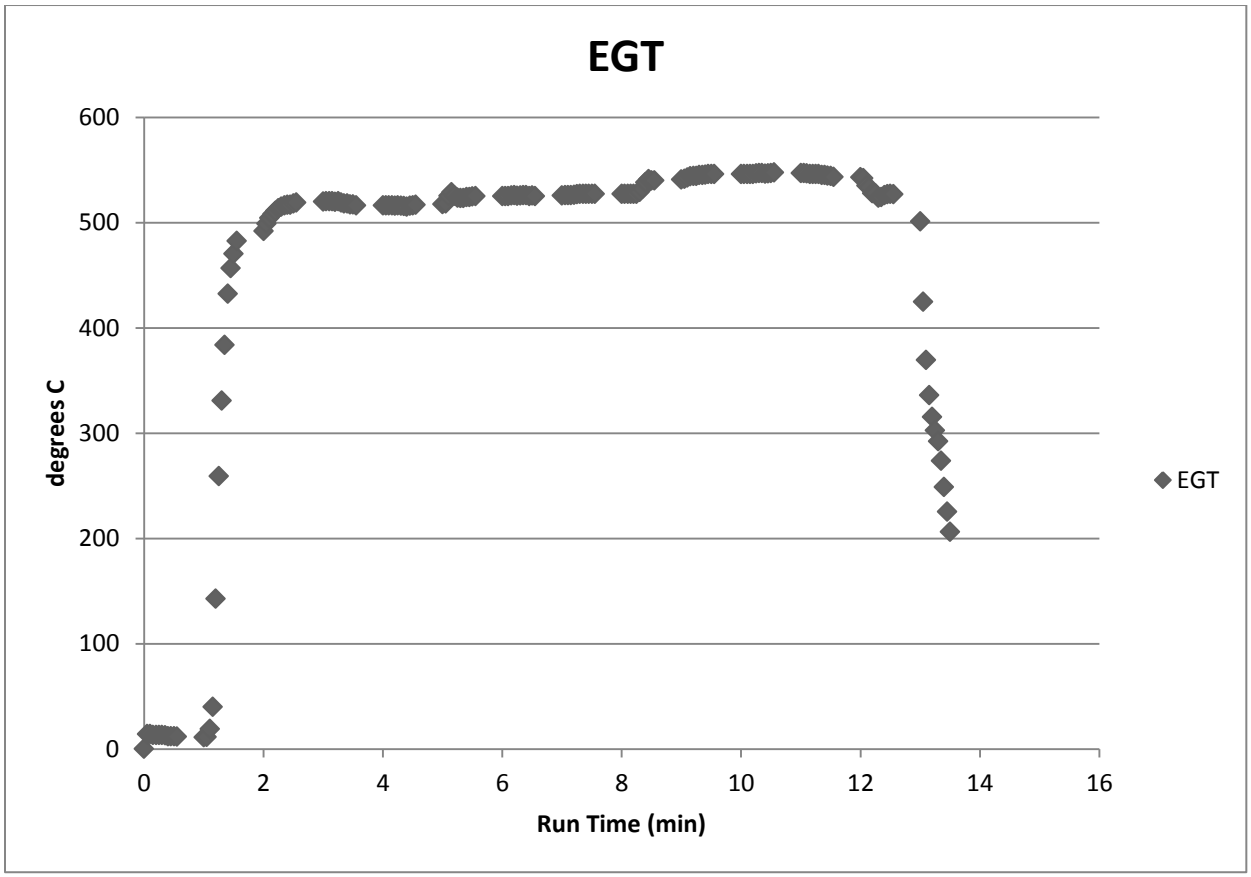

NO
g / kg fuel
Run Time (min)
NO
0
0.5
1
1.5
2
2.5
3
0
2
4
6
8
10
12
14
16

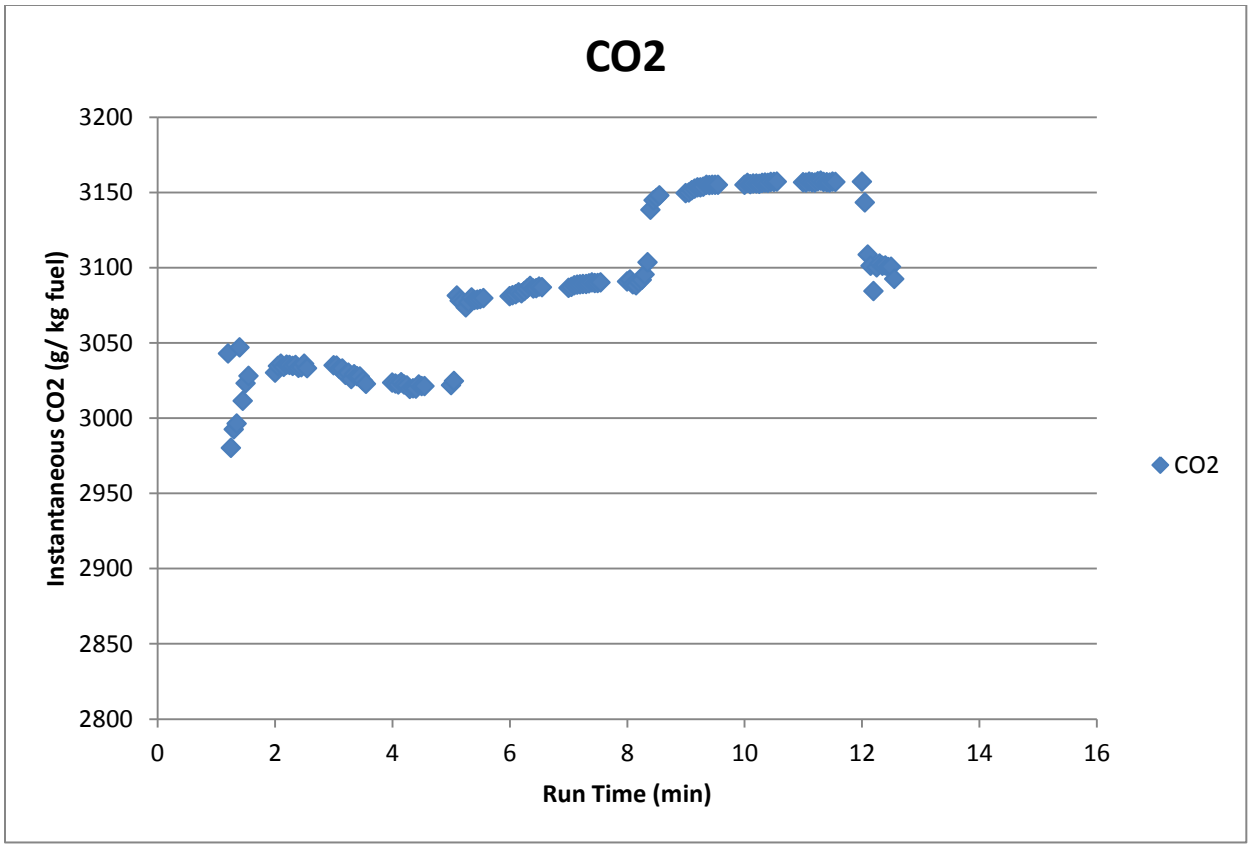

NO2
g / kg fuel
Run Time (min)
NO2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
2
4
6
8
10
12
14
16

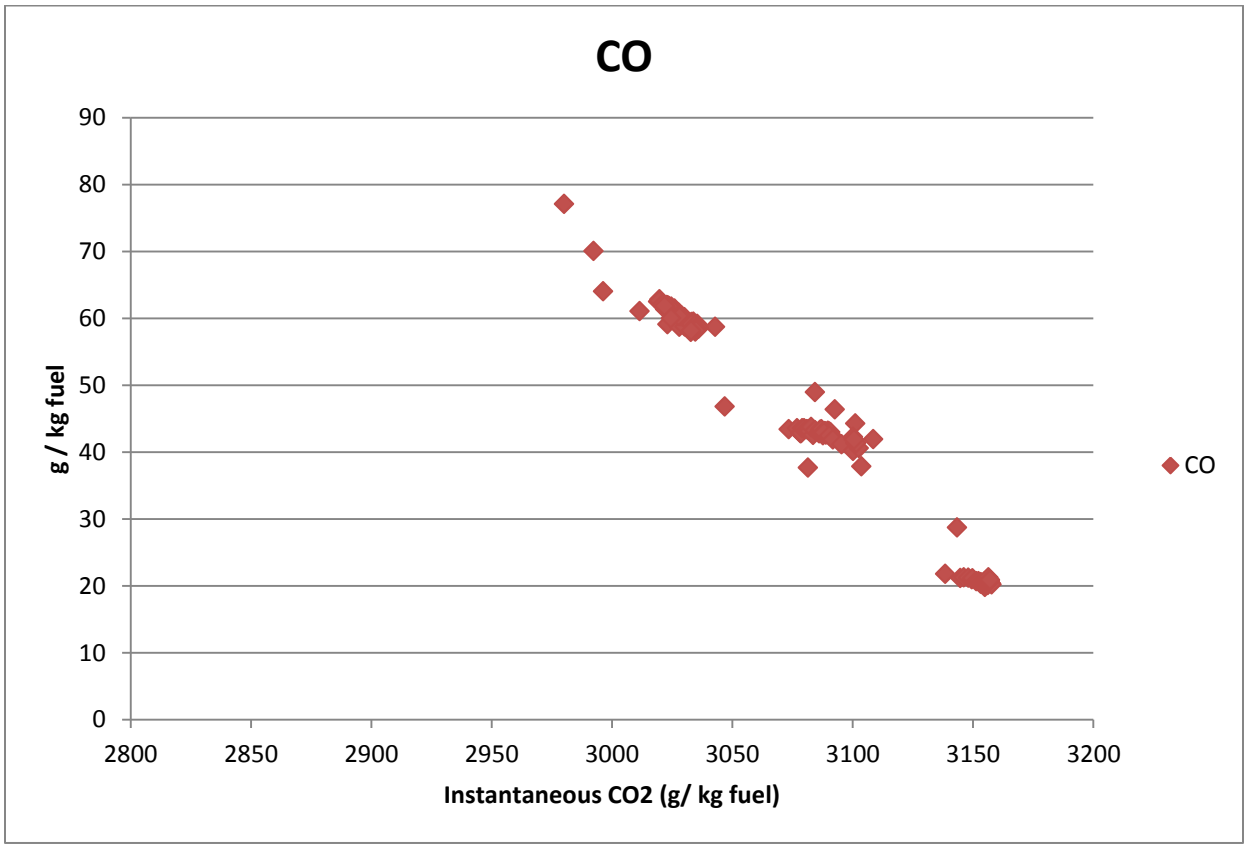

NOx
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
g / kg fuel
0
2
4
6
8
10
12
14
16
Run Time (min)
NOx

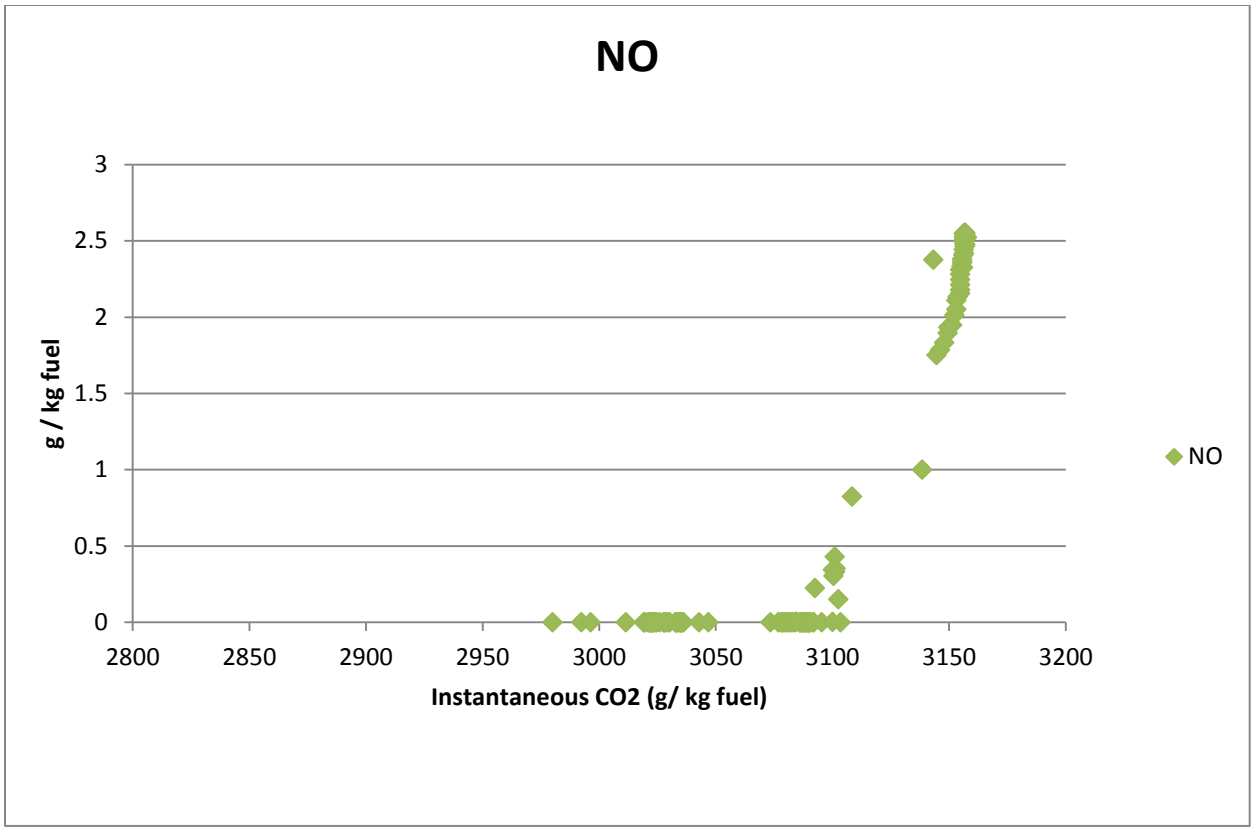

HC
35
30
25
20
15
10
5
0
g / kg fuel
0
2
4
6
8
10
12
14
16
Run Time (min)
HC

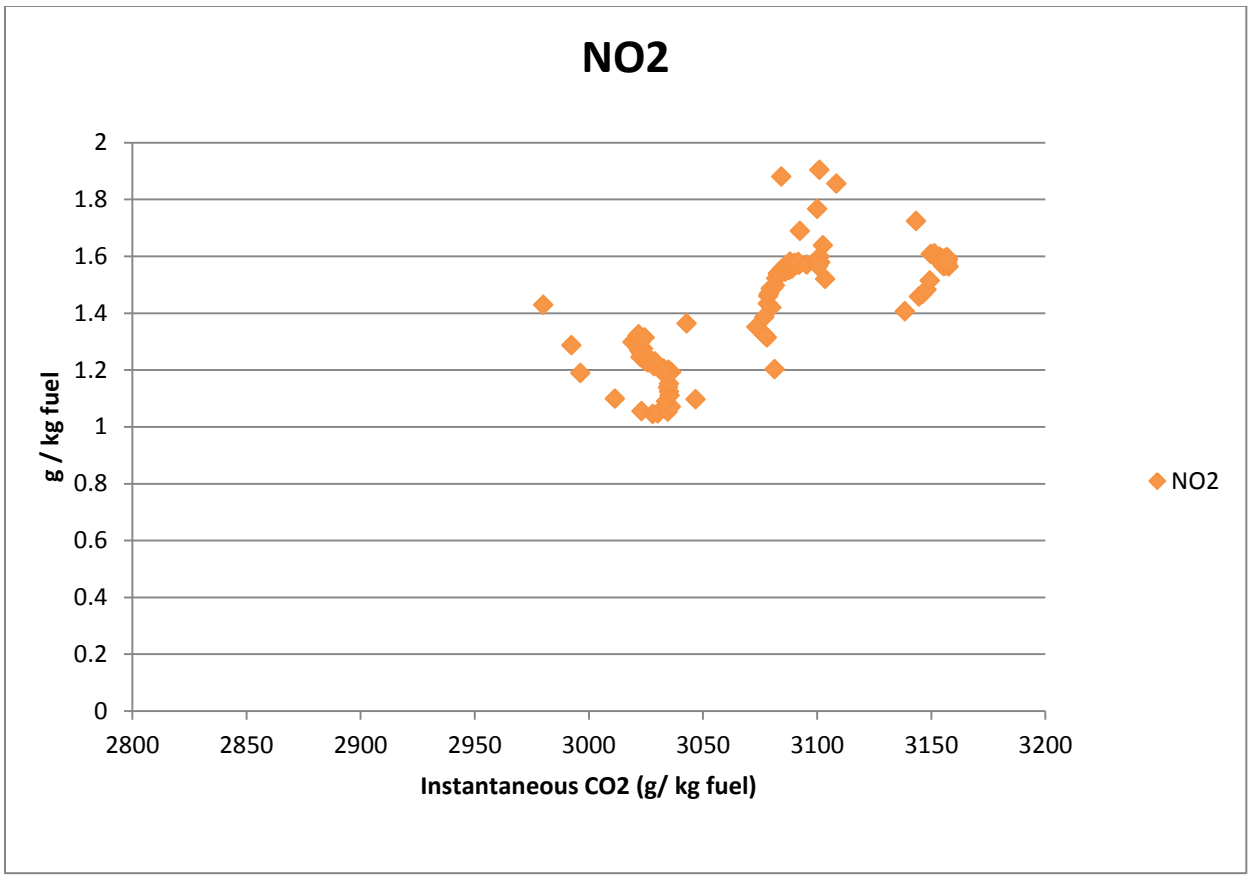

O2
16000
14000
12000
10000
8000
6000
4000
2000
0
g / kg fuel
0
2
4
6
8
10
12
14
16
Run Time (min)
O2

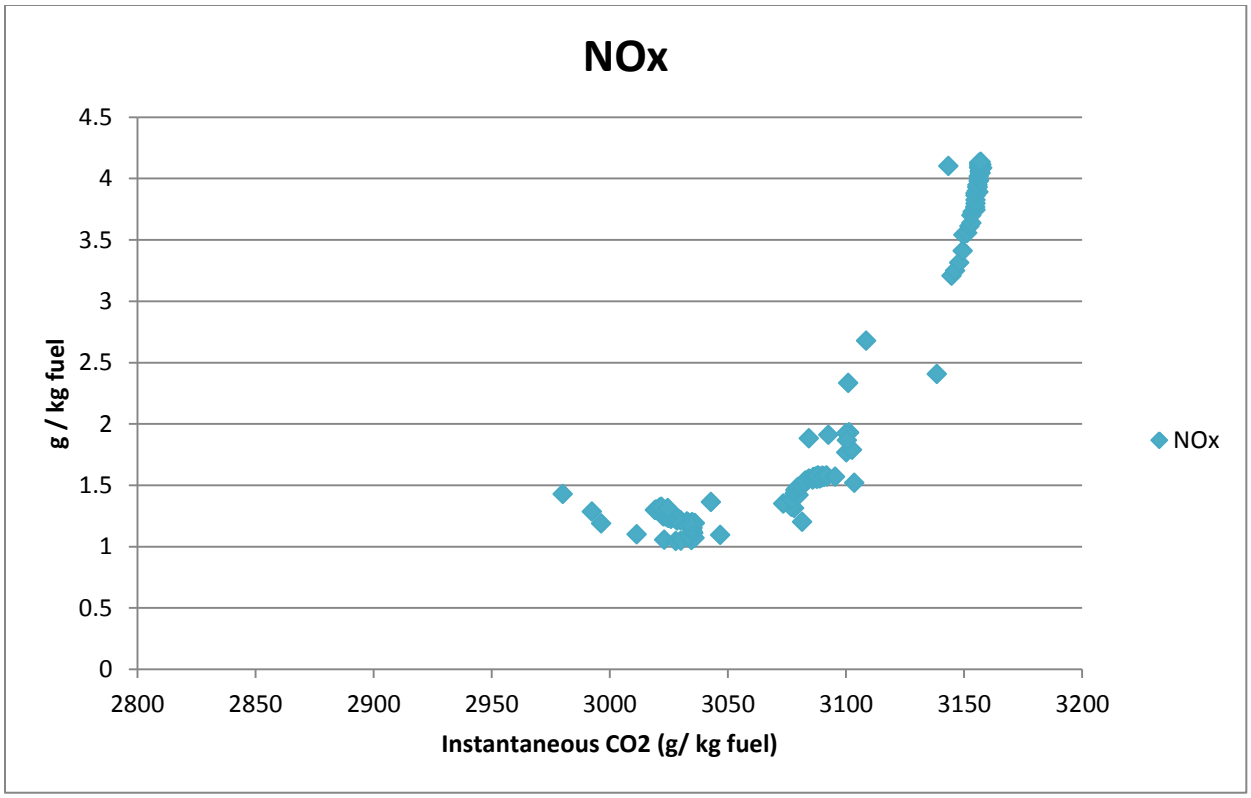

EGT
600
500
400
300
200
100
0
degrees C
0
2
4
6
8
10
12
14
16
Run Time (min)
EGT

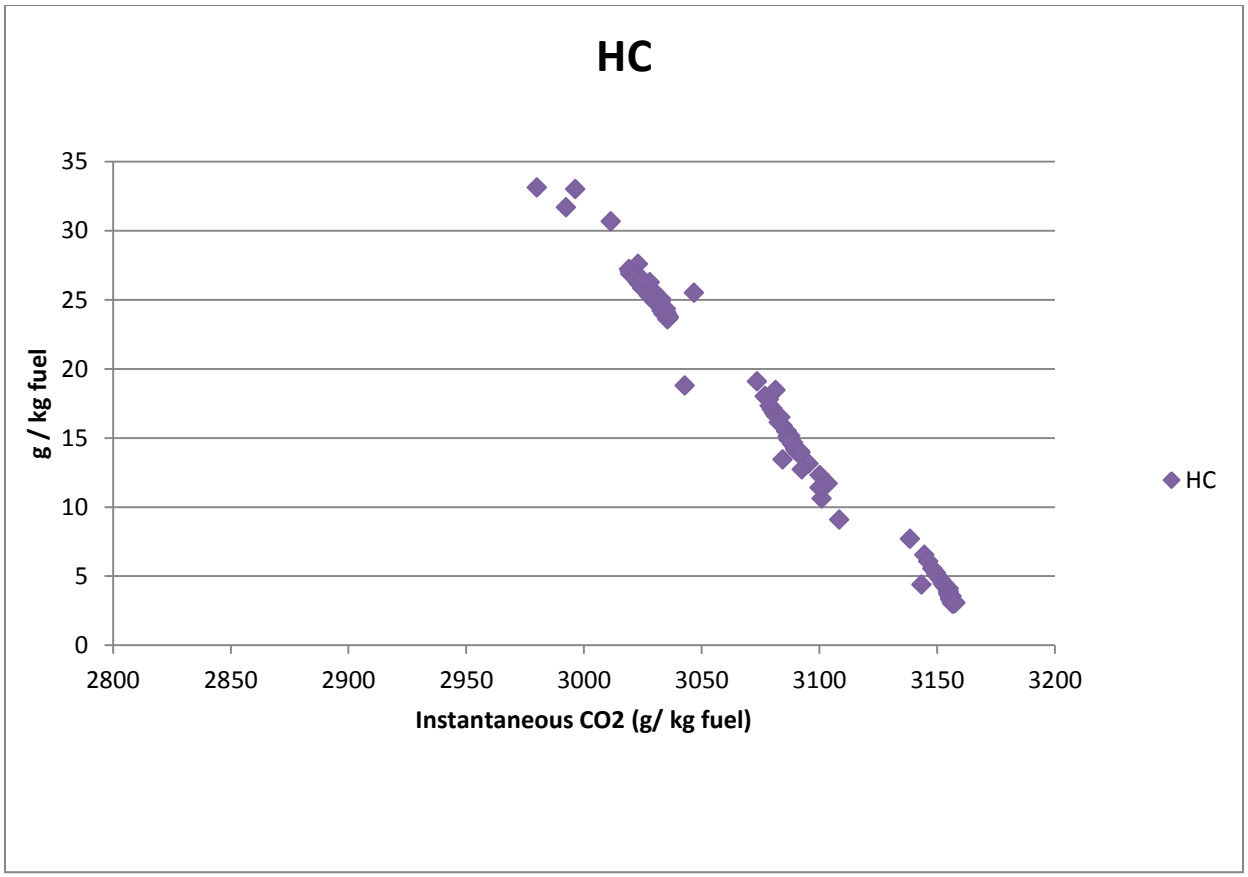

CO2
3200
3150
3100
3050
3000
2950
2900
2850
2800
Instantaneous CO2 (g/ kg fuel)
0
2
4
6
8
10
12
14
16
Run Time (min)
CO2


CO
90
80
70
60
50
40
30
20
10
0
g / kg fuel
2800
2850
2900
2950
3000
3050
3100
3150
3200
Instantaneous CO2 (g/ kg fuel)
CO


NO
3
2.5
2
1.5
1
0.5
0
g / kg fuel
2800
2850
2900
2950
3000
3050
3100
3150
3200
Instantaneous CO2 (g/ kg fuel)
NO

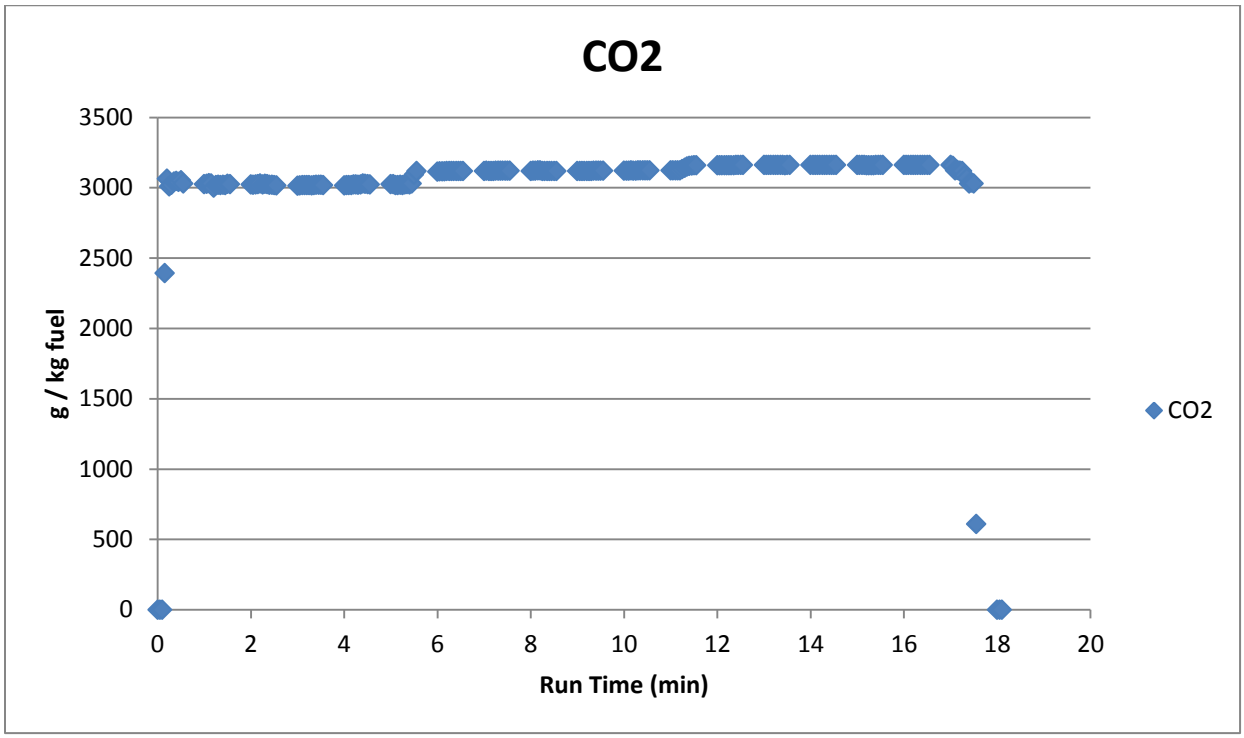

NO2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
g / kg fuel
2800
2850
2900
2950
3000
3050
3100
3150
3200
Instantaneous CO2 (g/ kg fuel)
NO2

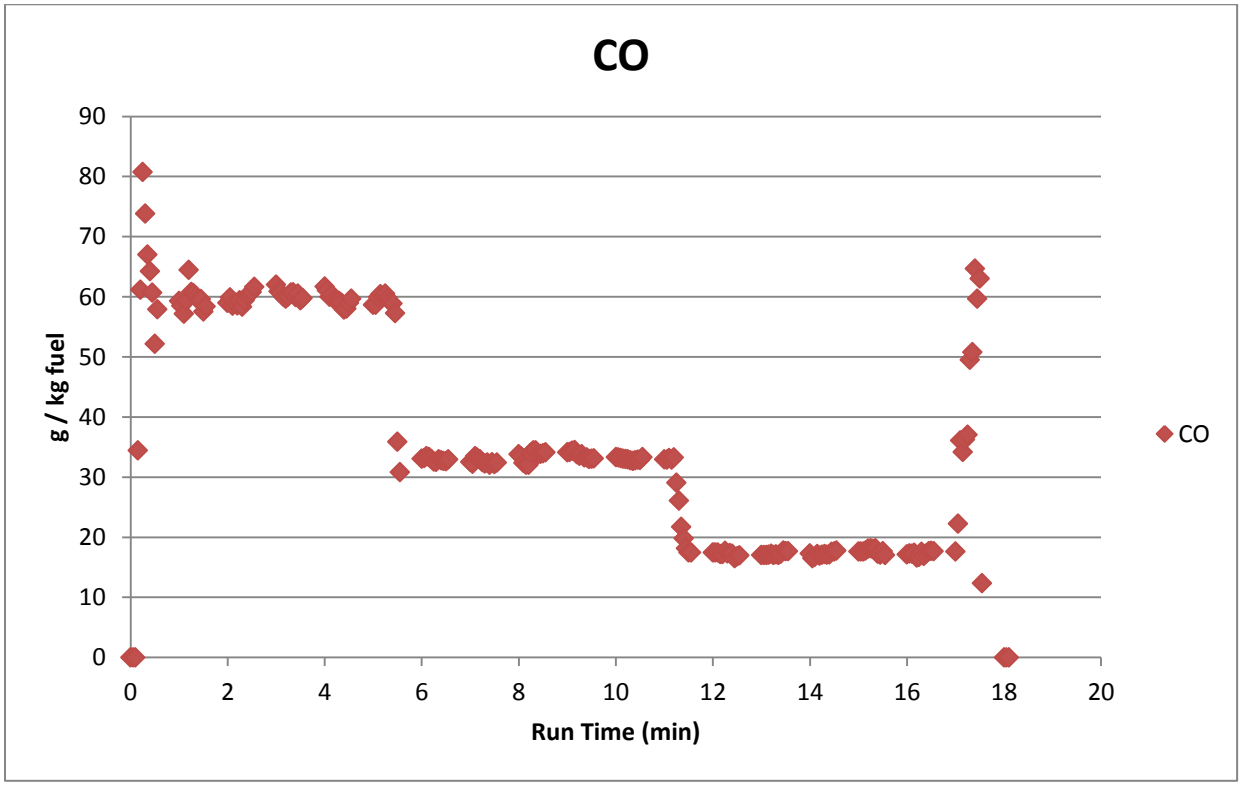

NOx
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
g / kg fuel
2800
2850
2900
2950
3000
3050
3100
3150
3200
Instantaneous CO2 (g/ kg fuel)
NOx

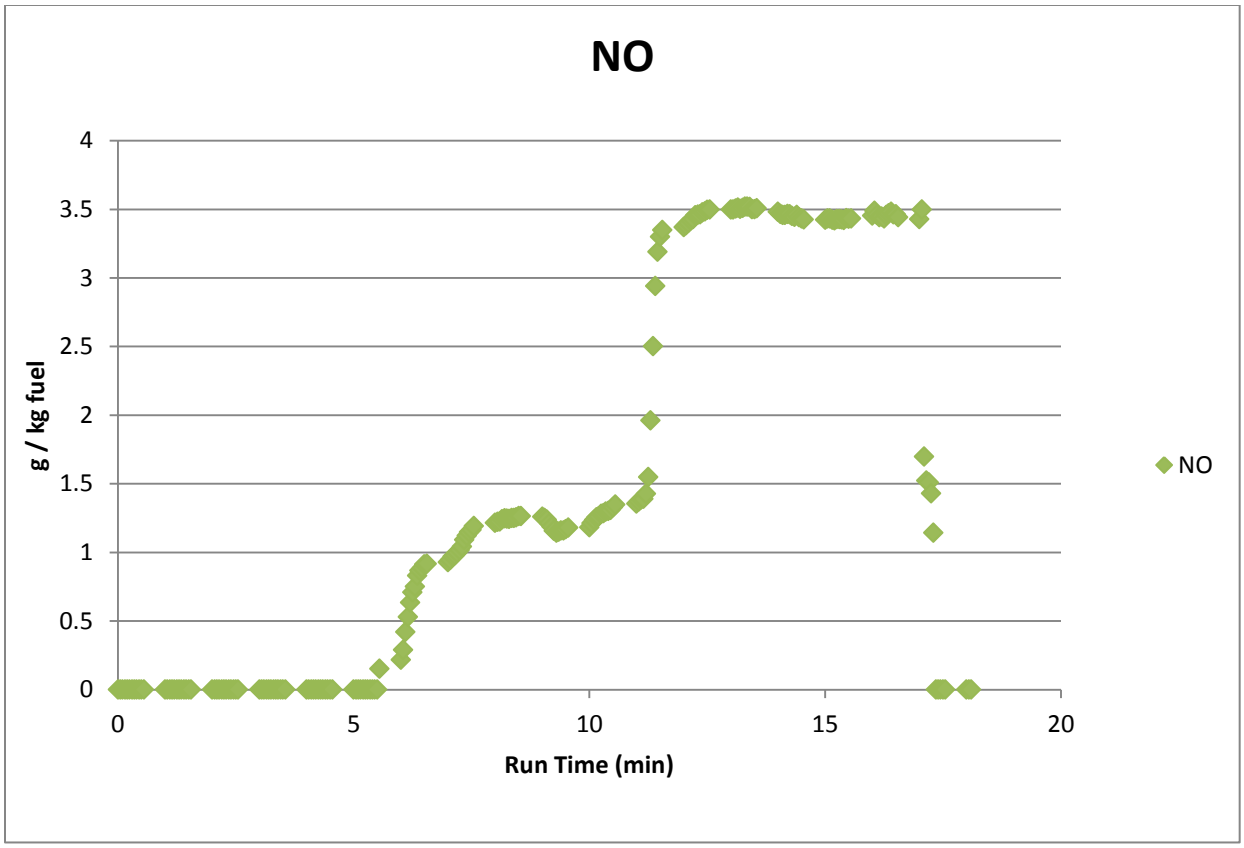

HC
35
30
25
20
15
10
5
0
g / kg fuel
2800
2850
2900
2950
3000
3050
3100
3150
3200
Instantaneous CO2 (g/ kg fuel)
HC

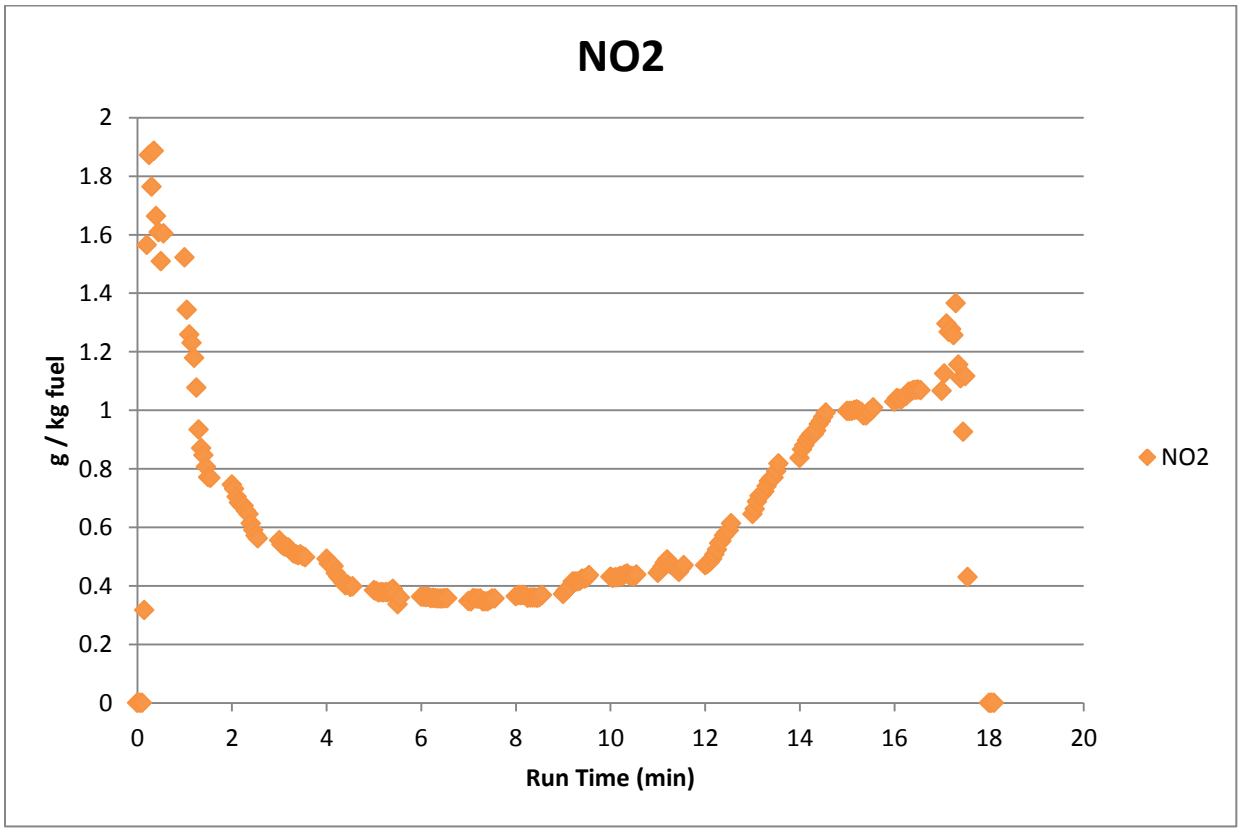
Appendix C: Results from 7/10/2012 Salina Sampling

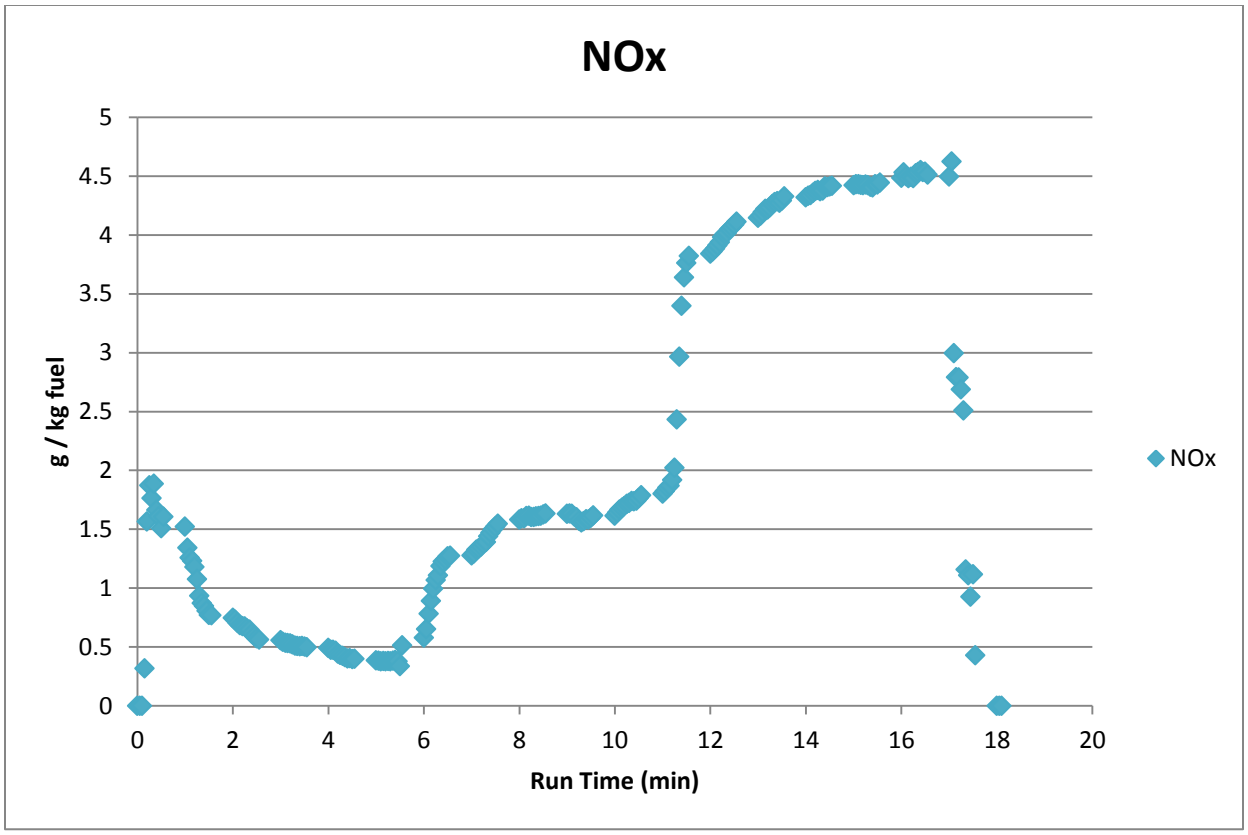
Salina2 NCF 7/10/2012 PT6

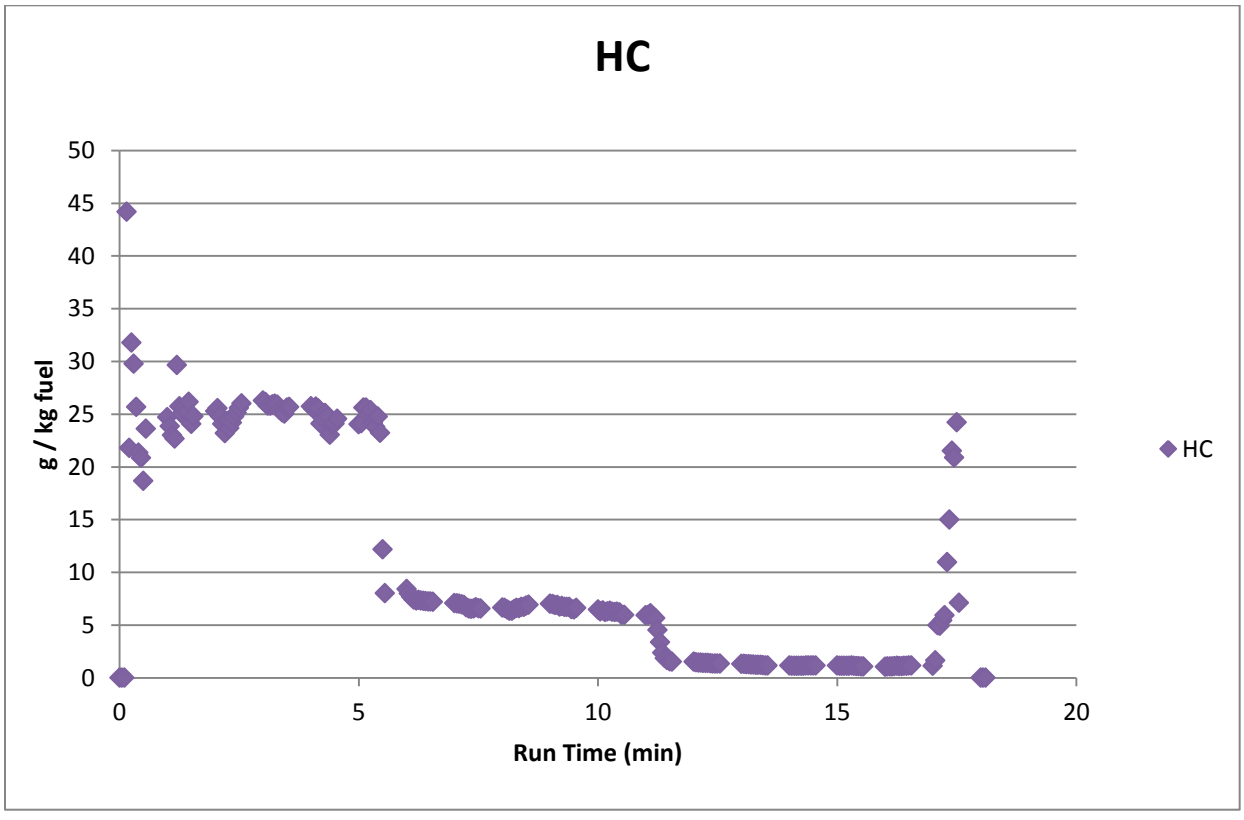


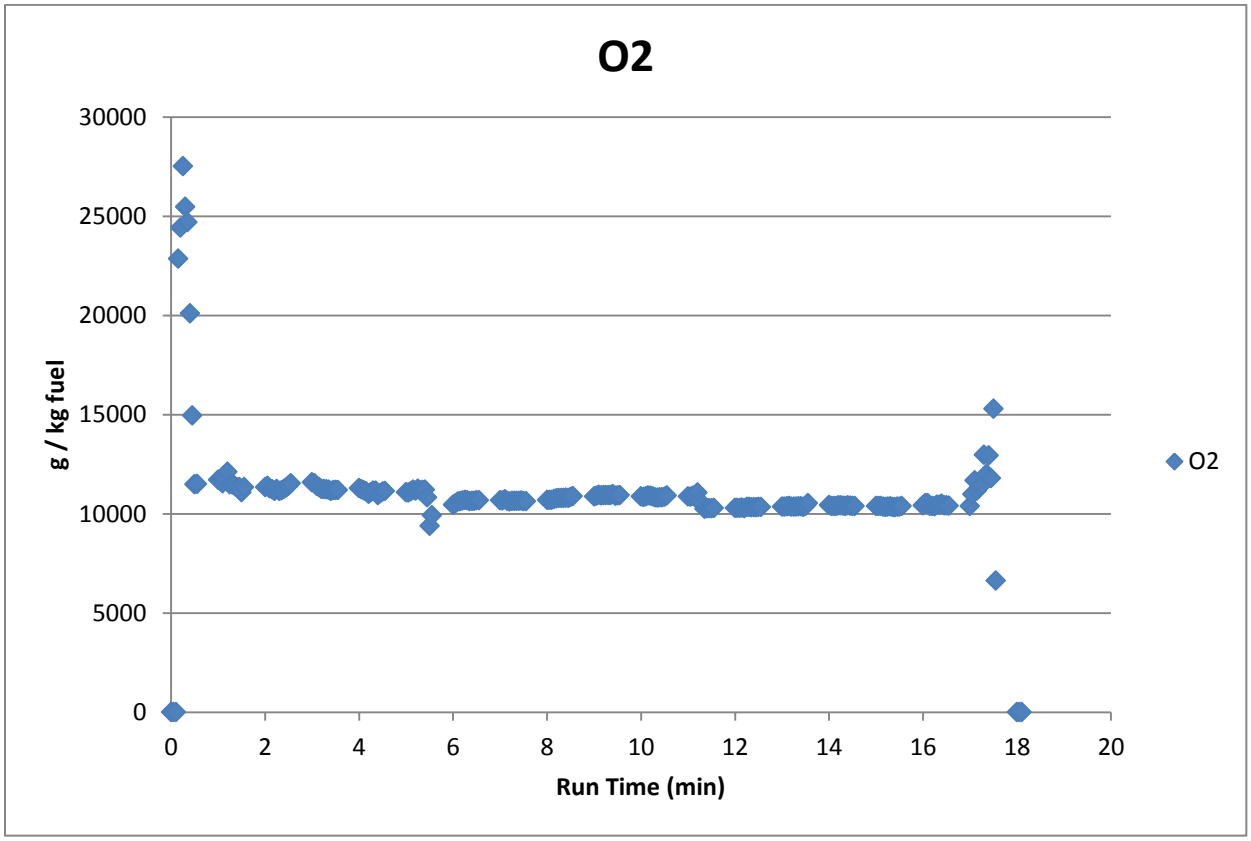


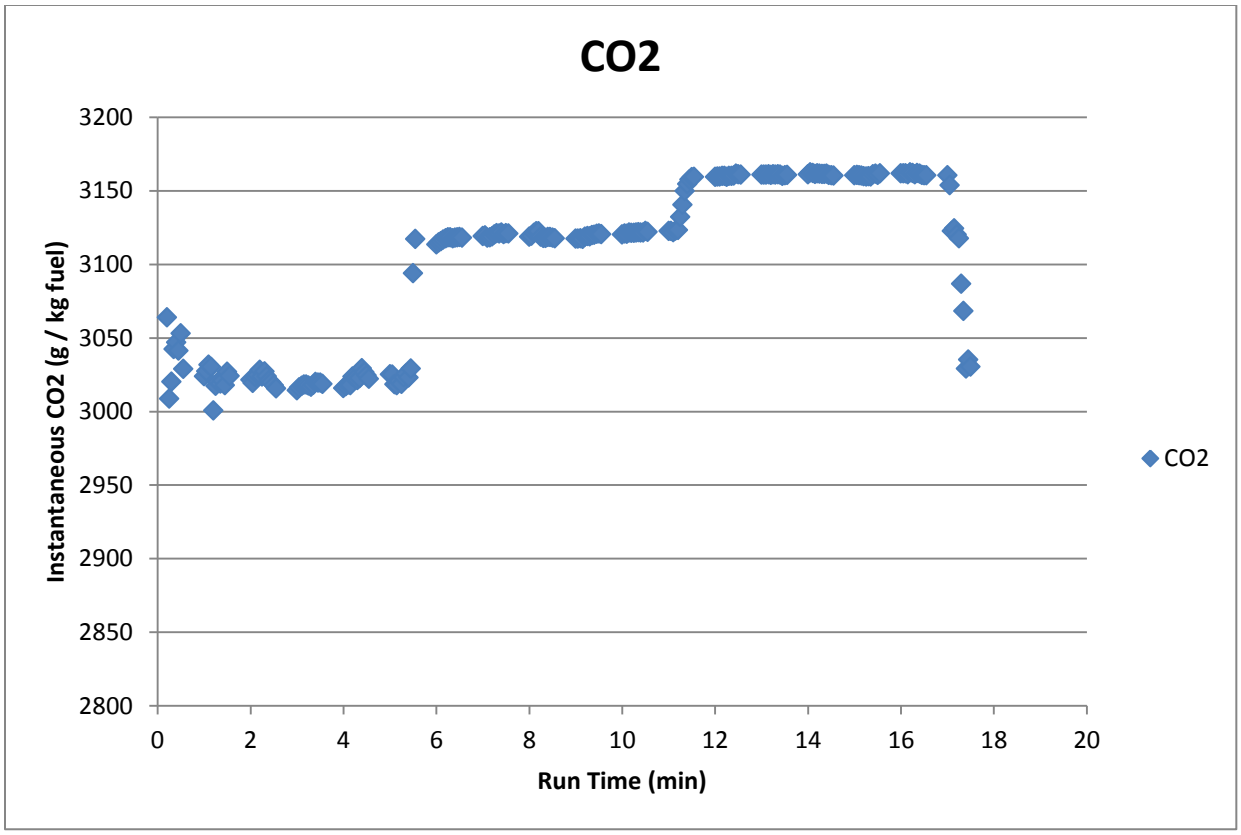

NO
g / kg fuel
Run Time (min)
NO
0
0.5
1
1.5
2
2.5
3
3.5
4
0
5
10
15
20

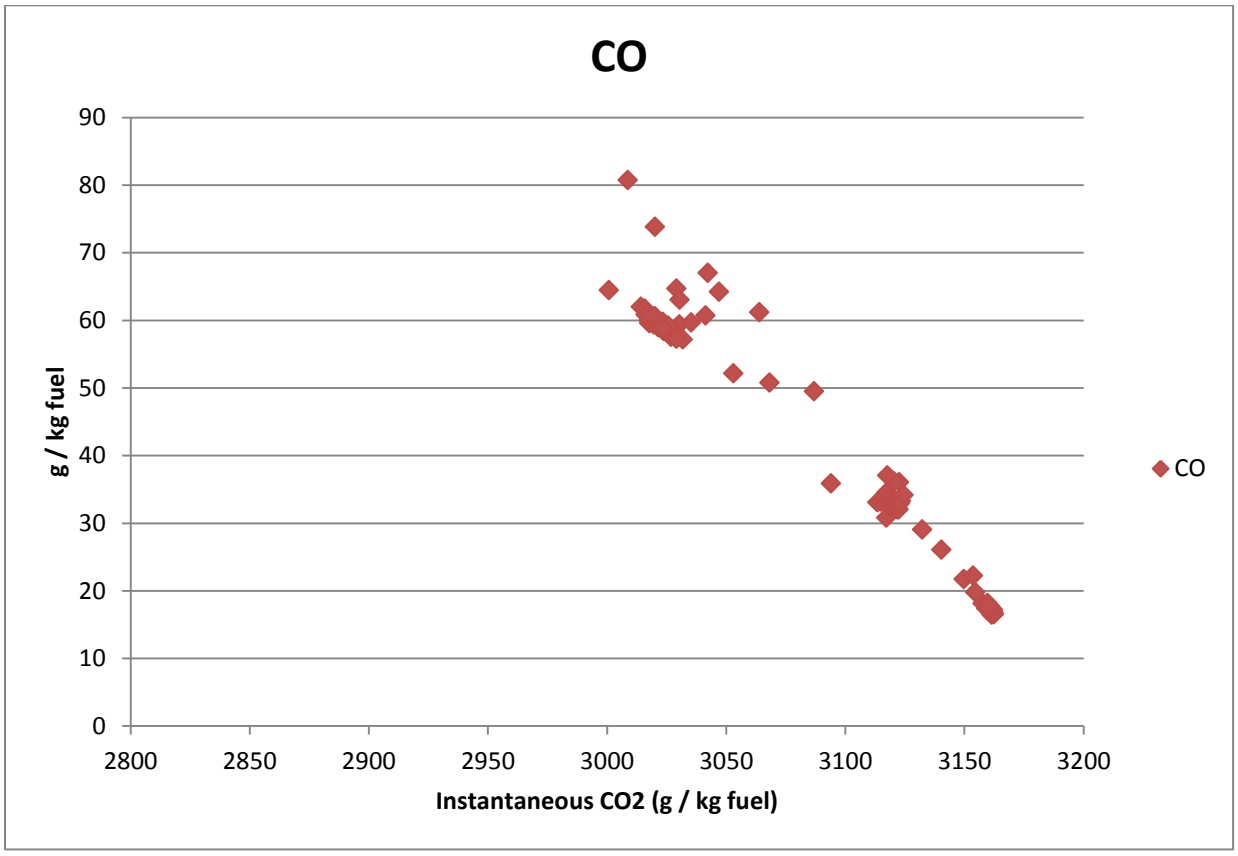

NO2
g / kg fuel
Run Time (min)
NO2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
2
4
6
8
10
12
14
16
18
20

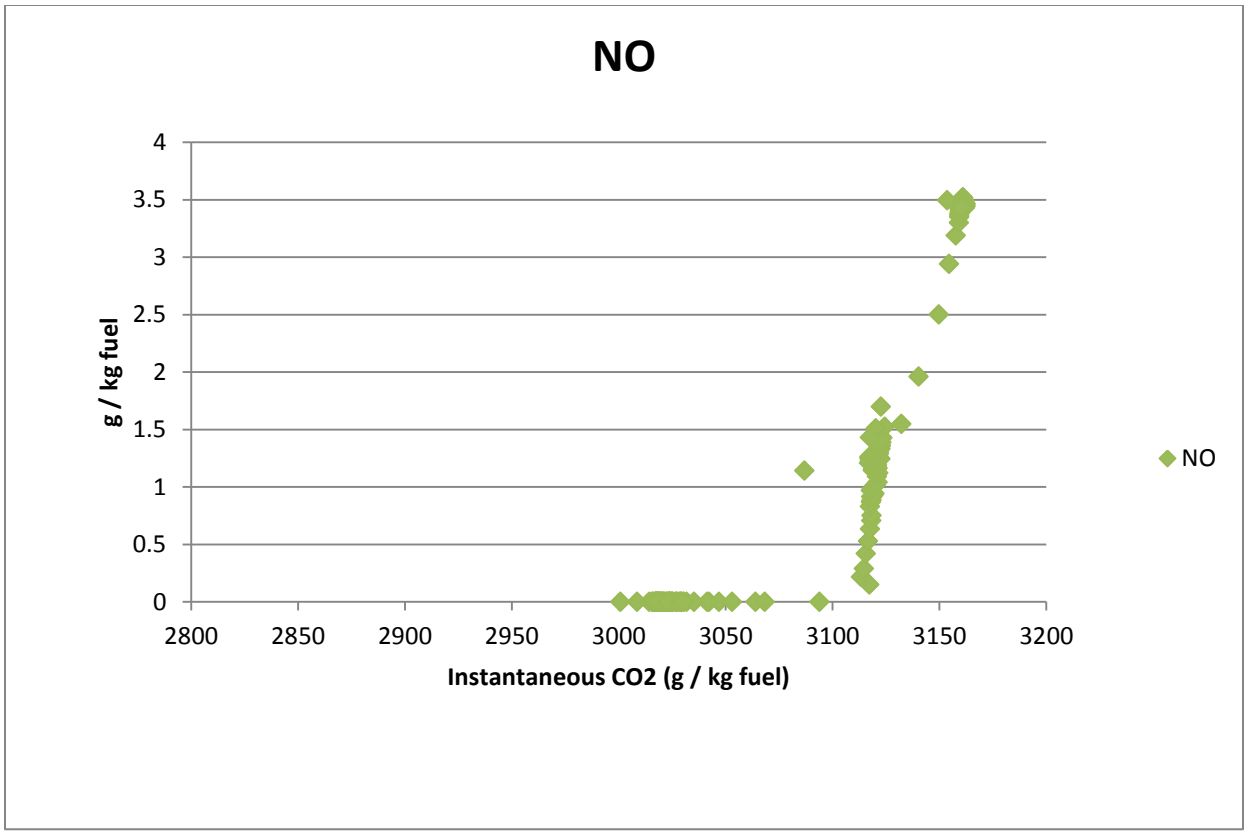

NOx
g / kg fuel
Run Time (min)
NOx
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
2
4
6
8
10
12
14
16
18
20

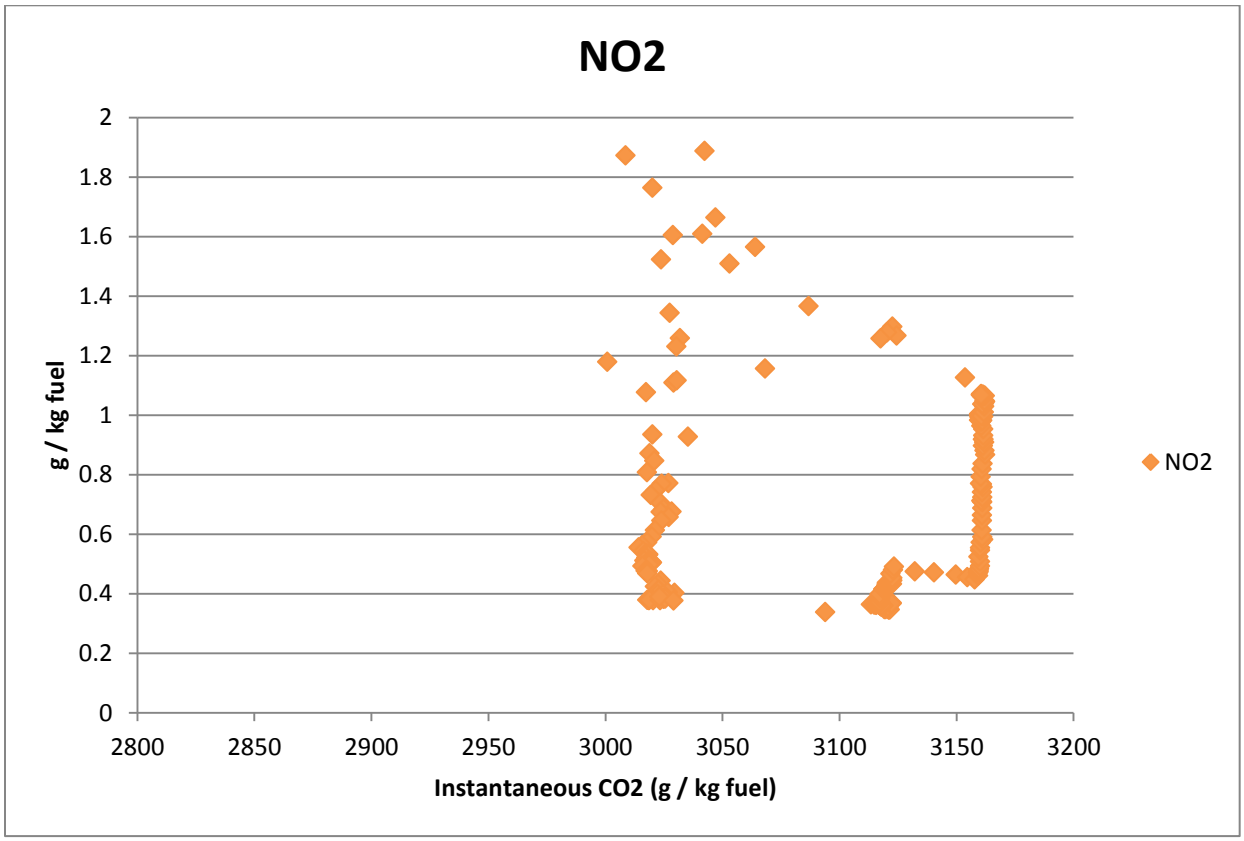

HC
g / kg fuel
Run Time (min)
HC
0
5
10
15
20
25
30
35
40
45
50
0
5
10
15
20

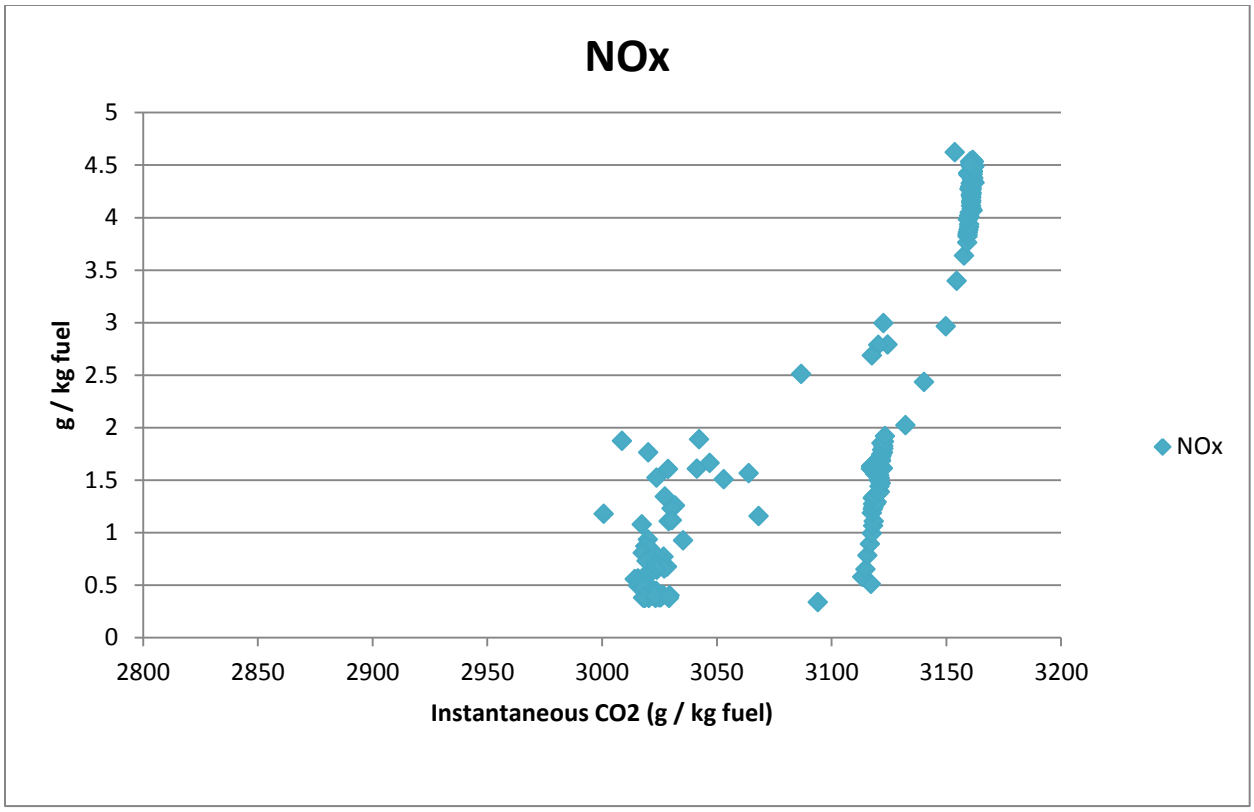

O2
30000
25000
20000
15000
10000
5000
0
g / kg fuel
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
O2

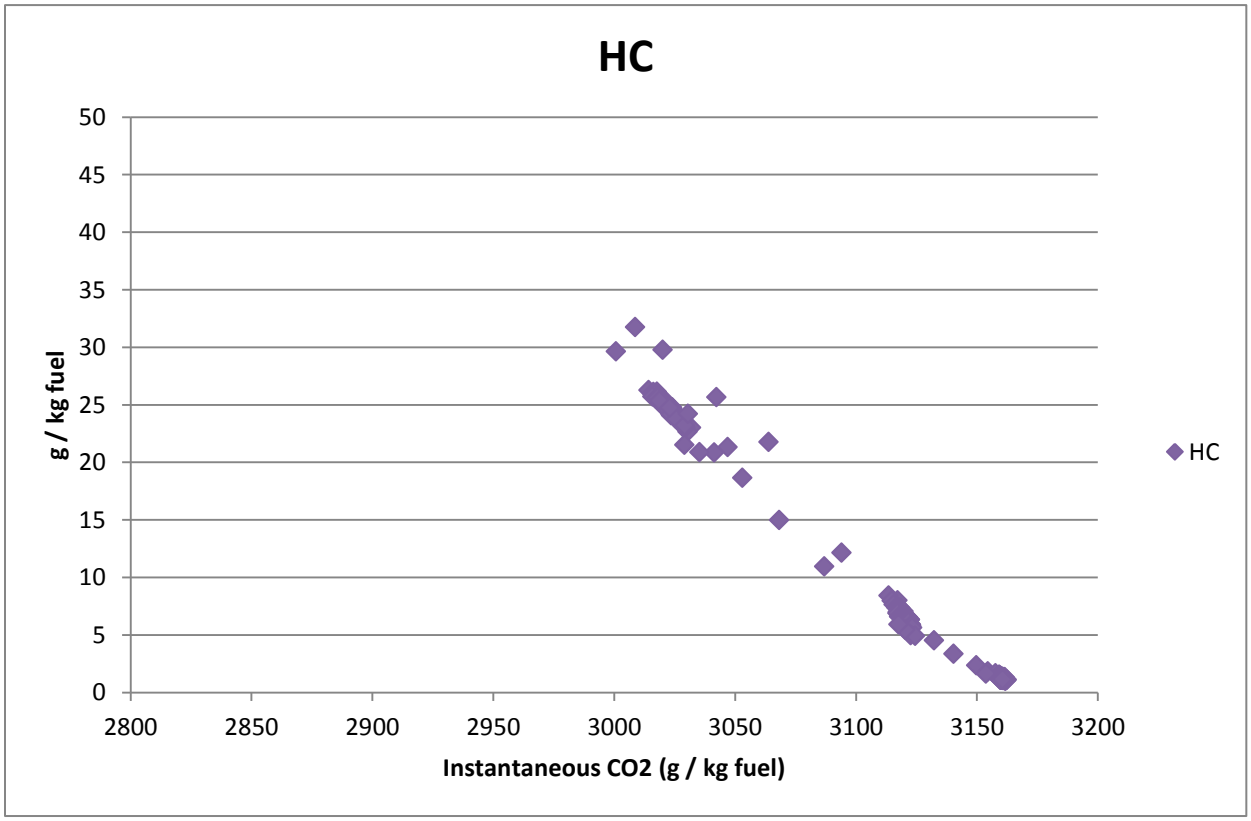

CO2
Instantaneous CO2 (g / kg fuel)
3200
3150
3100
3050
3000
2950
2900
2850
2800
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
CO2


CO
g / kg fuel
90
80
70
60
50
40
30
20
10
0
2800
2850
2900
2950
3000
3050
3100
3150
3200
Instantaneous CO2 (g / kg fuel)
CO

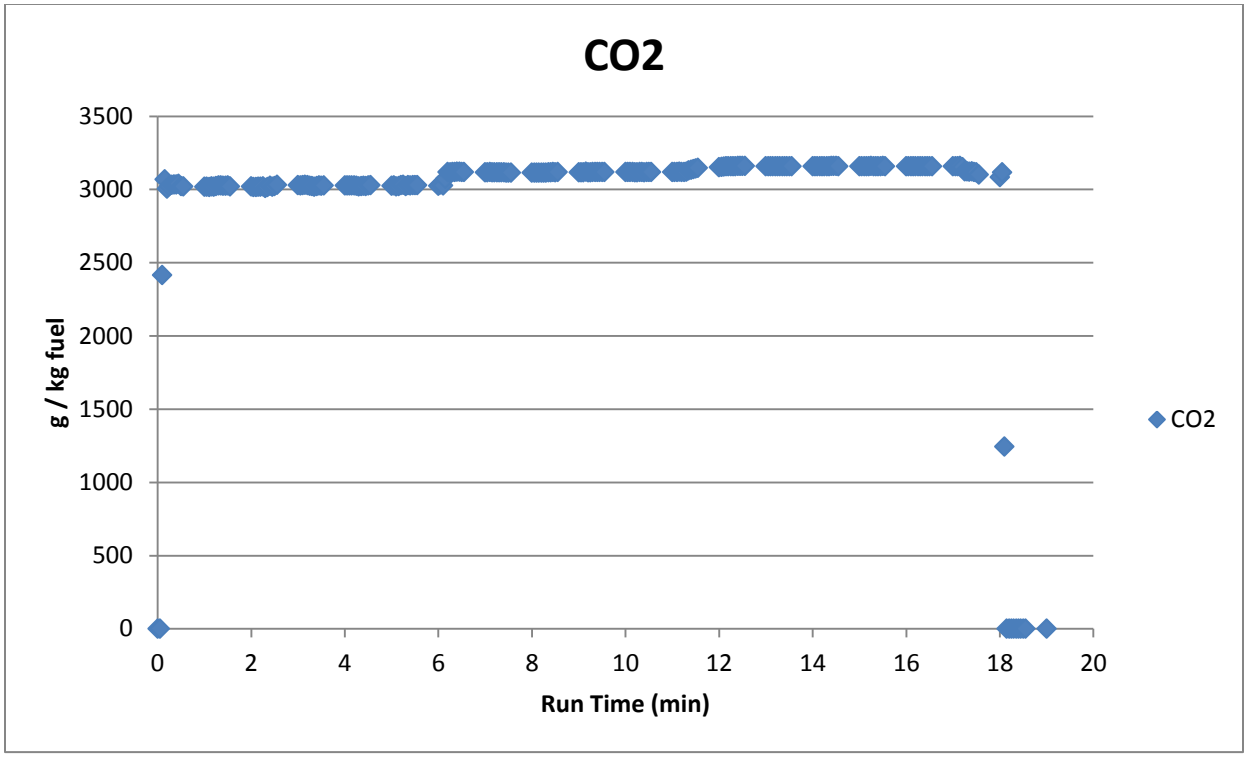

NO
g / kg fuel
4
3.5
3
2.5
2
1.5
1
0.5
0
2800
2850
2900
2950
3000
3050
3100
3150
3200
Instantaneous CO2 (g / kg fuel)
NO

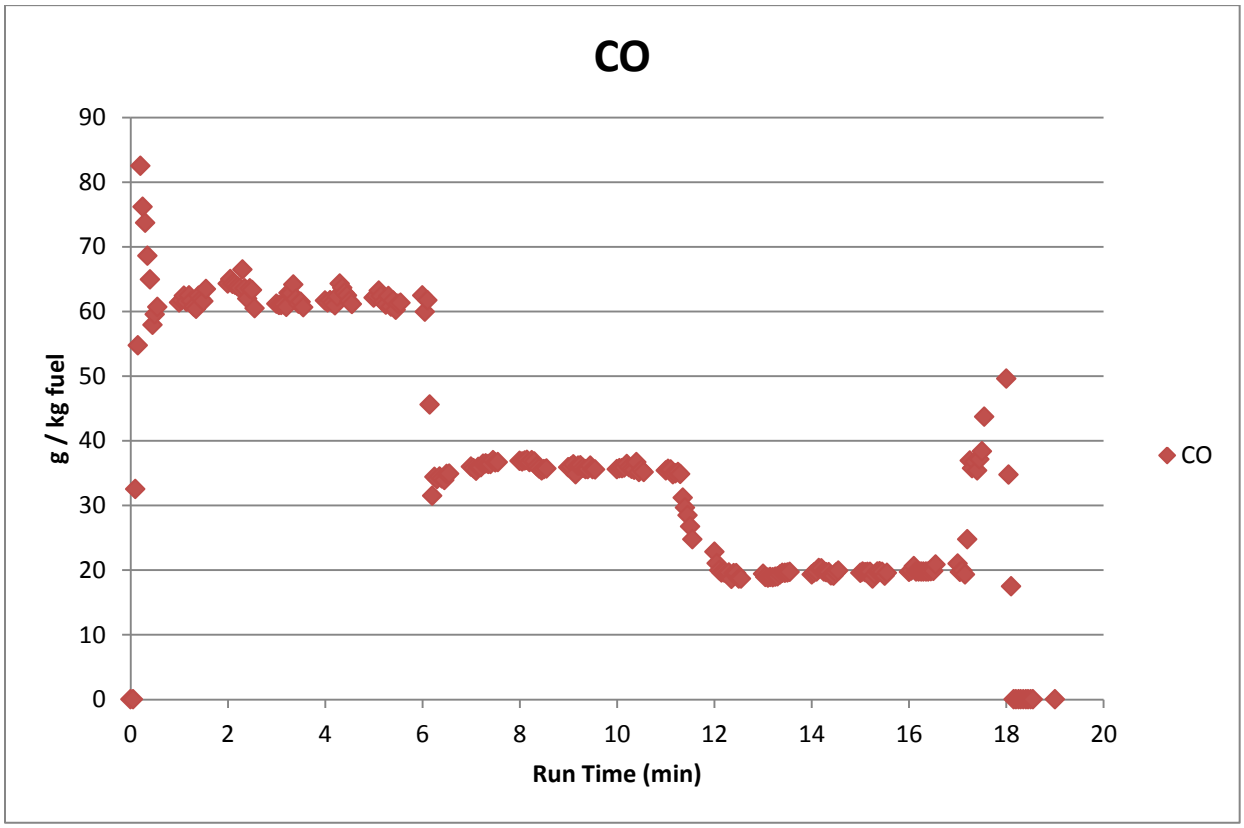

NO2
g / kg fuel
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
2800
2850
2900
2950
3000
3050
3100
3150
3200
Instantaneous CO2 (g / kg fuel)
NO2

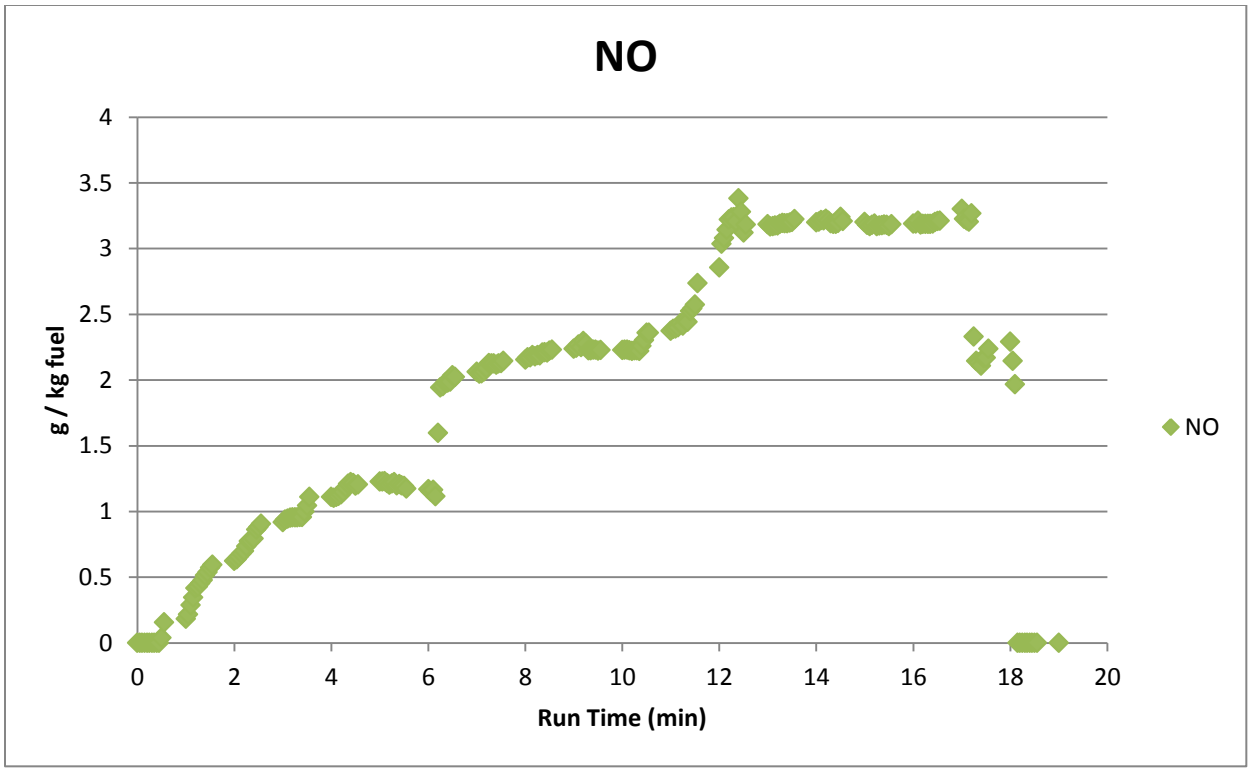

NOx
g / kg fuel
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
2800
2850
2900
2950
3000
3050
3100
3150
3200
Instantaneous CO2 (g / kg fuel)
NOx

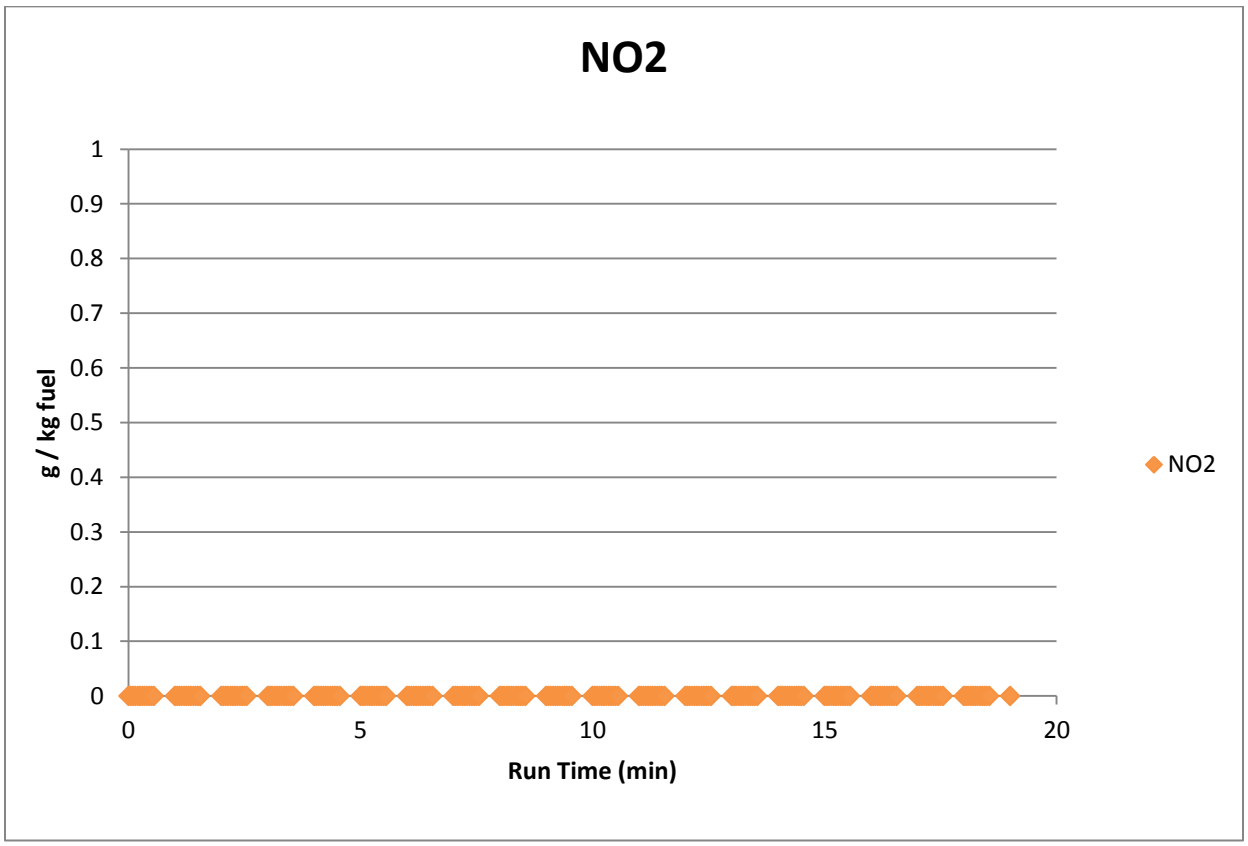

HC
g / kg fuel
50
45
40
35
30
25
20
15
10
5
0
2800
2850
2900
2950
3000
3050
3100
3150
3200
Instantaneous CO2 (g / kg fuel)
HC

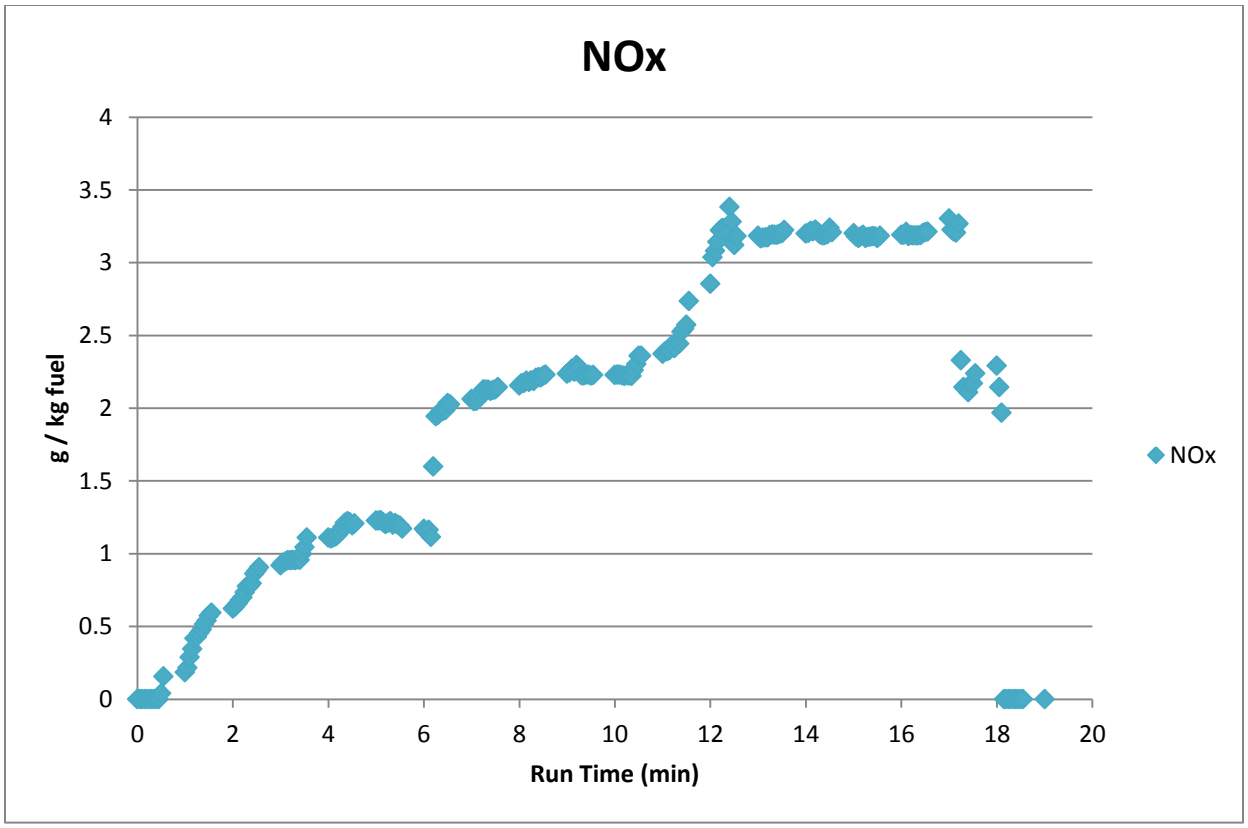
Salina2 CF 7/10/2012 PT6

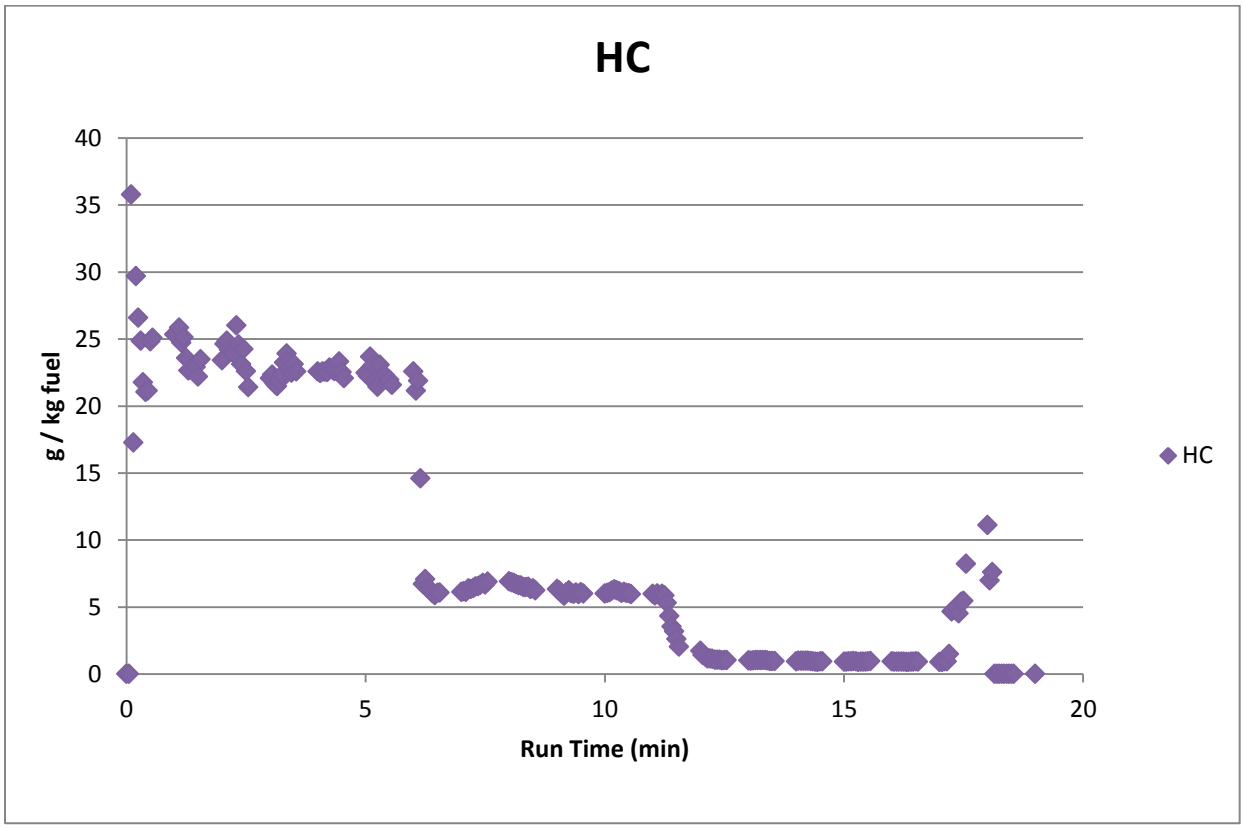


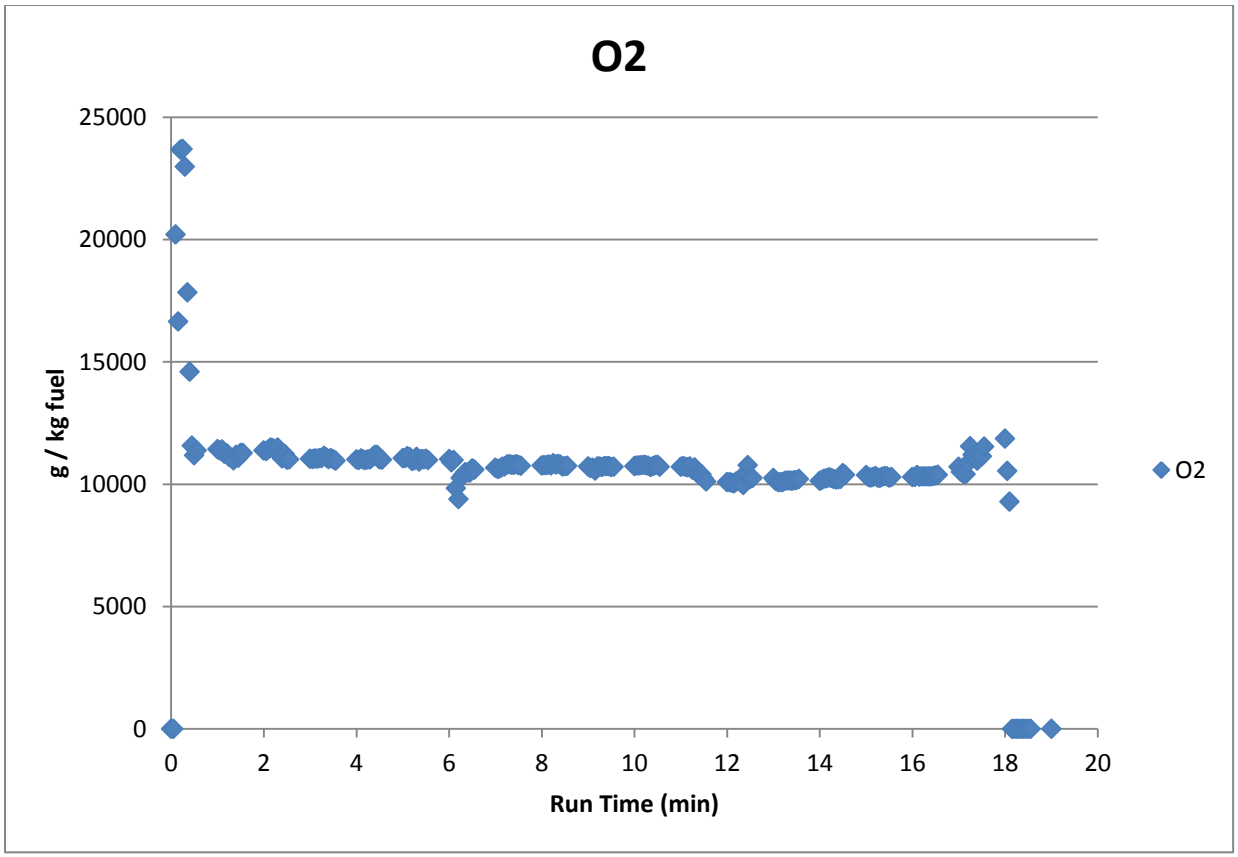


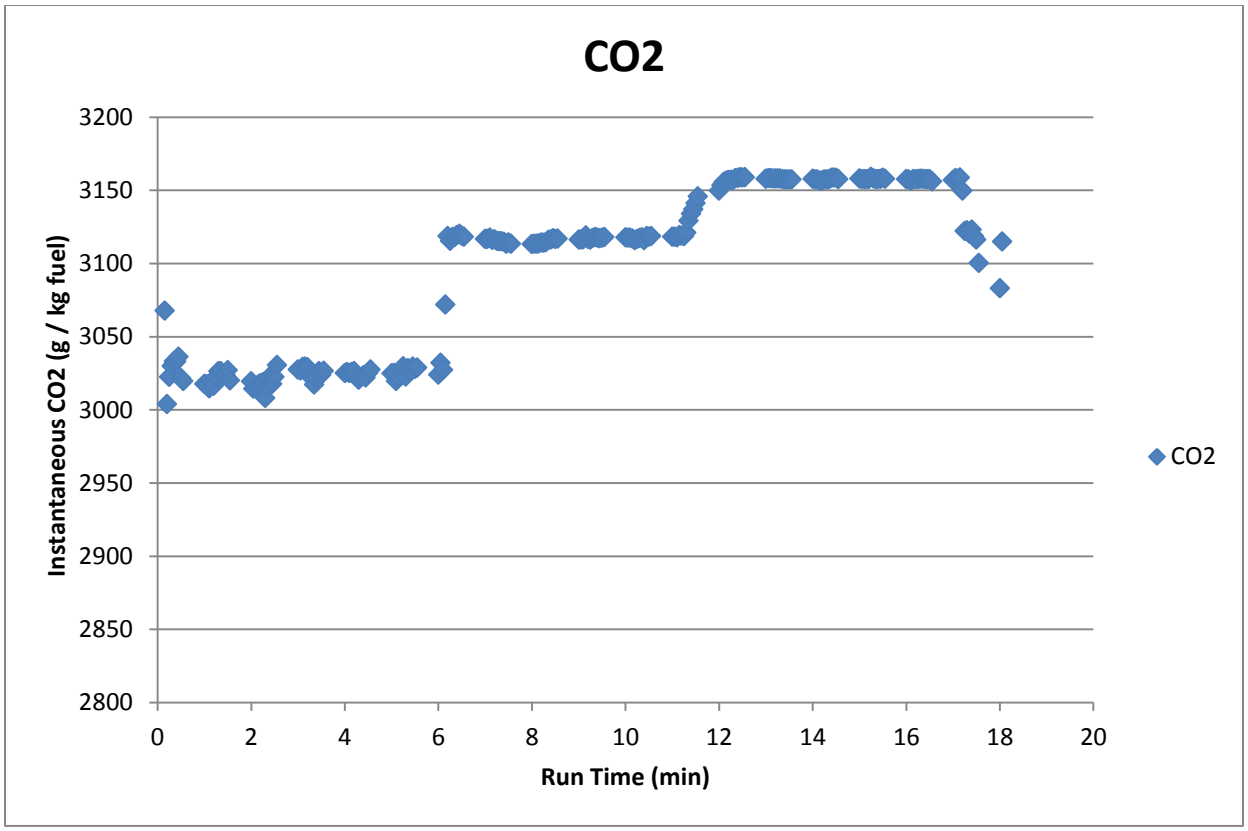

NO
g / kg fuel
4
3.5
3
2.5
2
1.5
1
0.5
0
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
NO

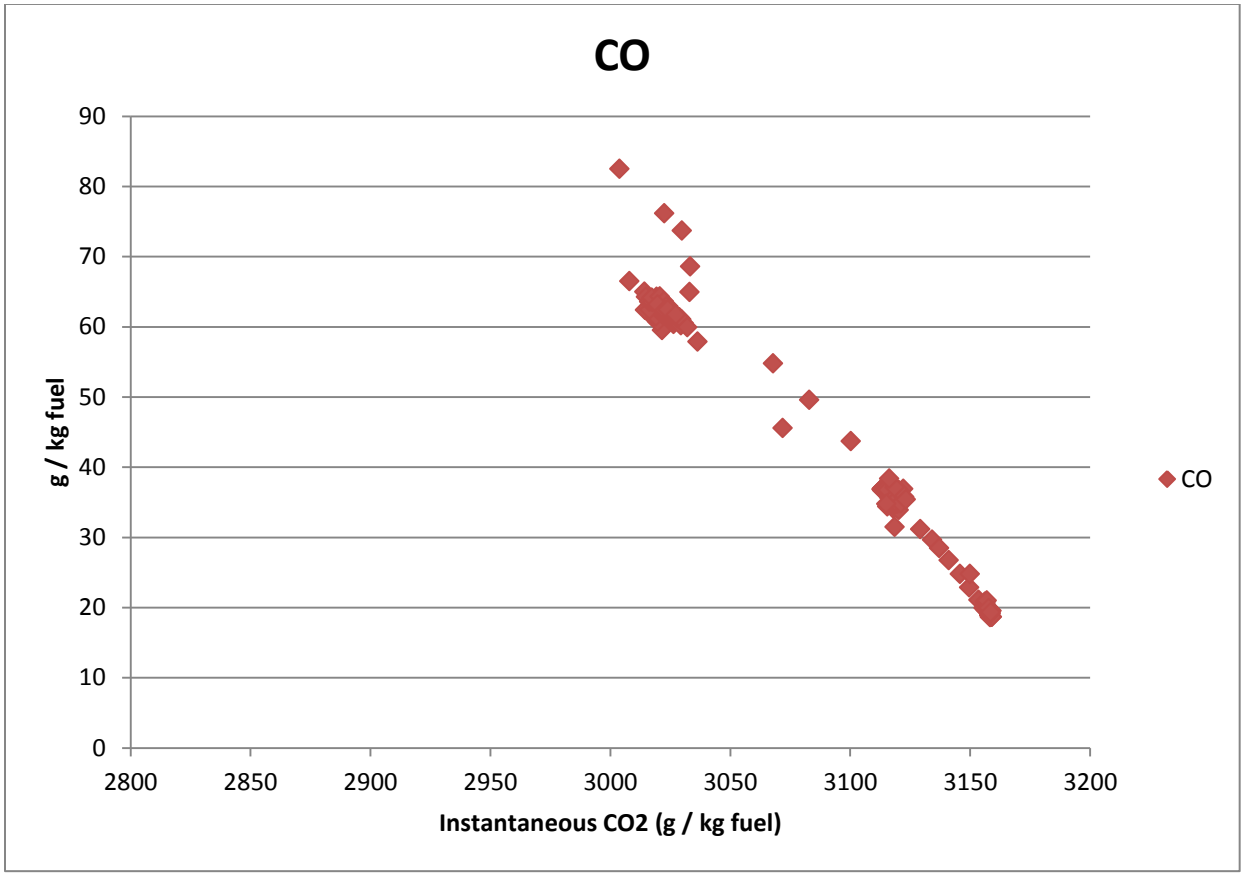

NO2
g / kg fuel
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20
Run Time (min)
NO2

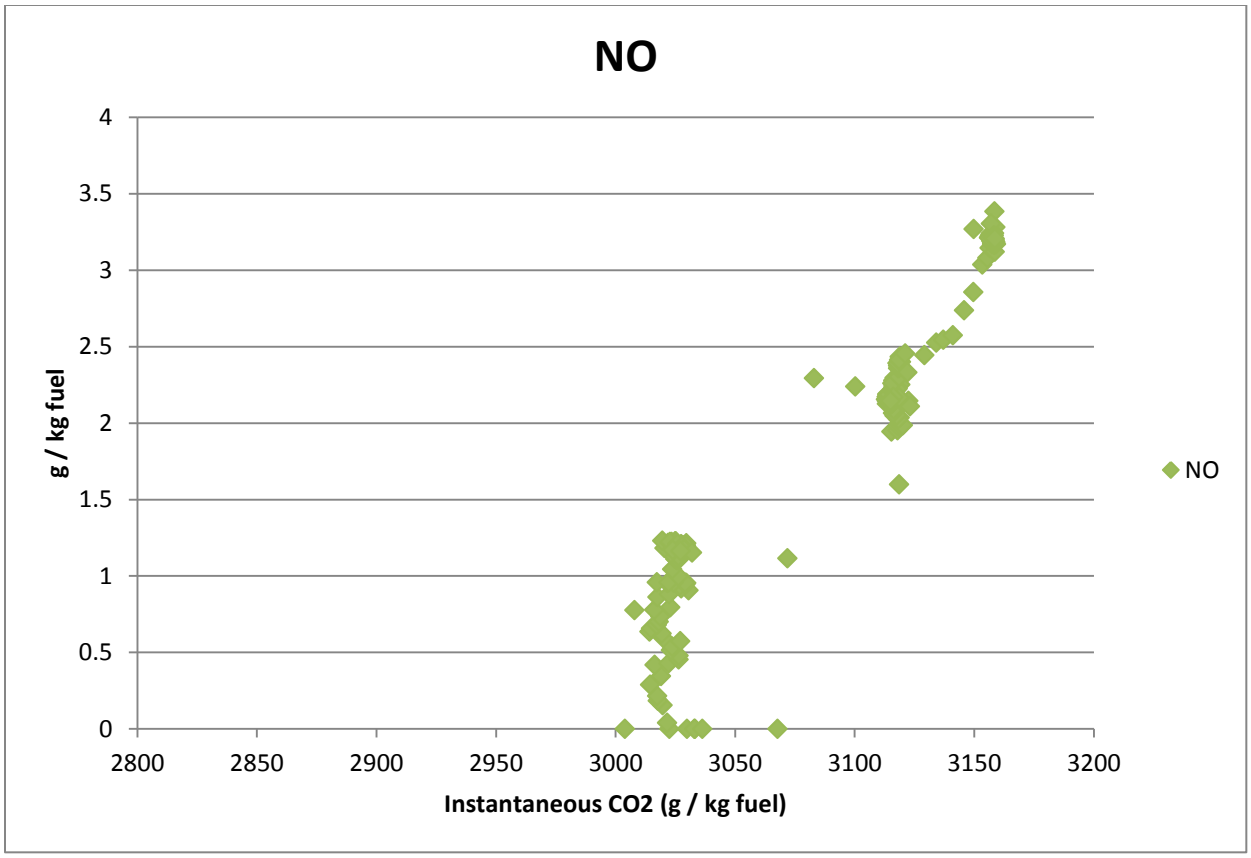

NOx
g / kg fuel
Run Time (min)
NOx
0
0.5
1
1.5
2
2.5
3
3.5
4
0
2
4
6
8
10
12
14
16
18
20

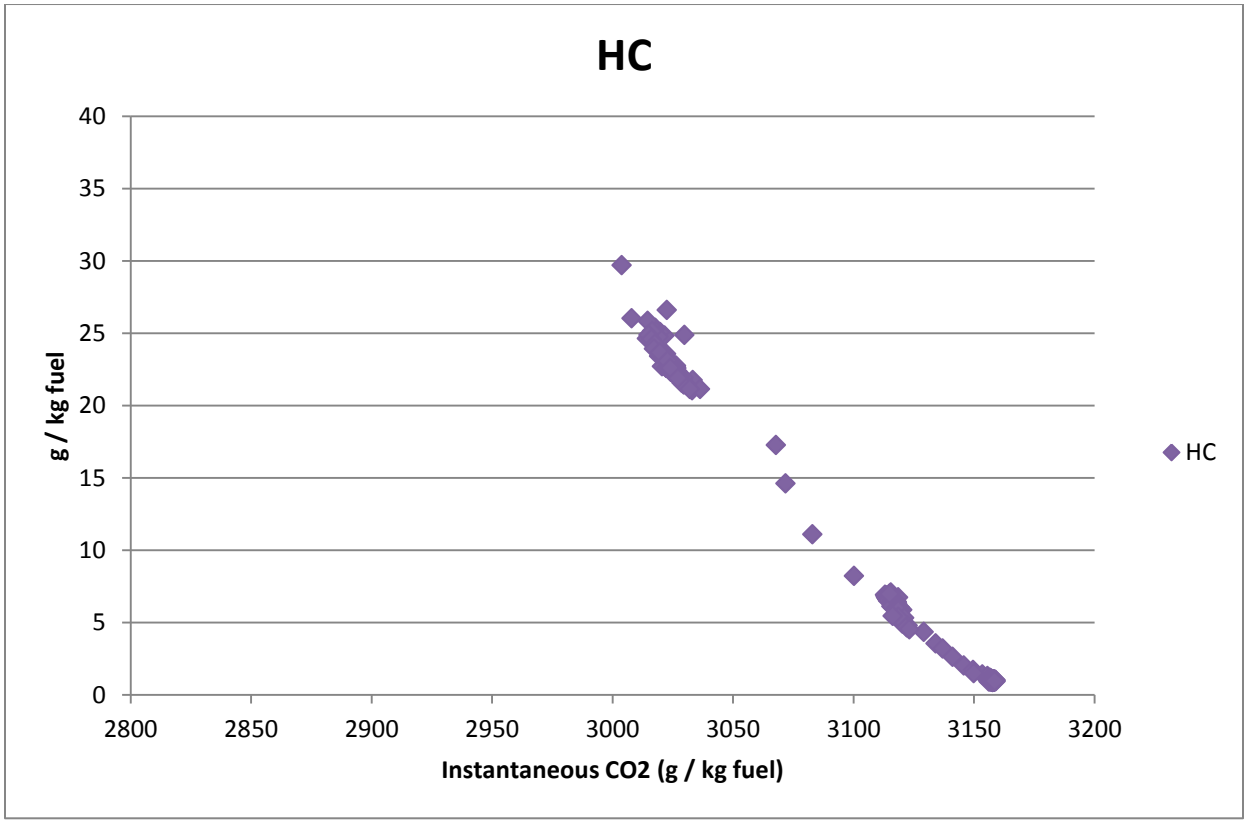

HC
g / kg fuel
Run Time (min)
HC
0
5
10
15
20
25
30
35
40
0
5
10
15
20


O2
25000
20000
15000
10000
5000
0
g / kg fuel
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
O2

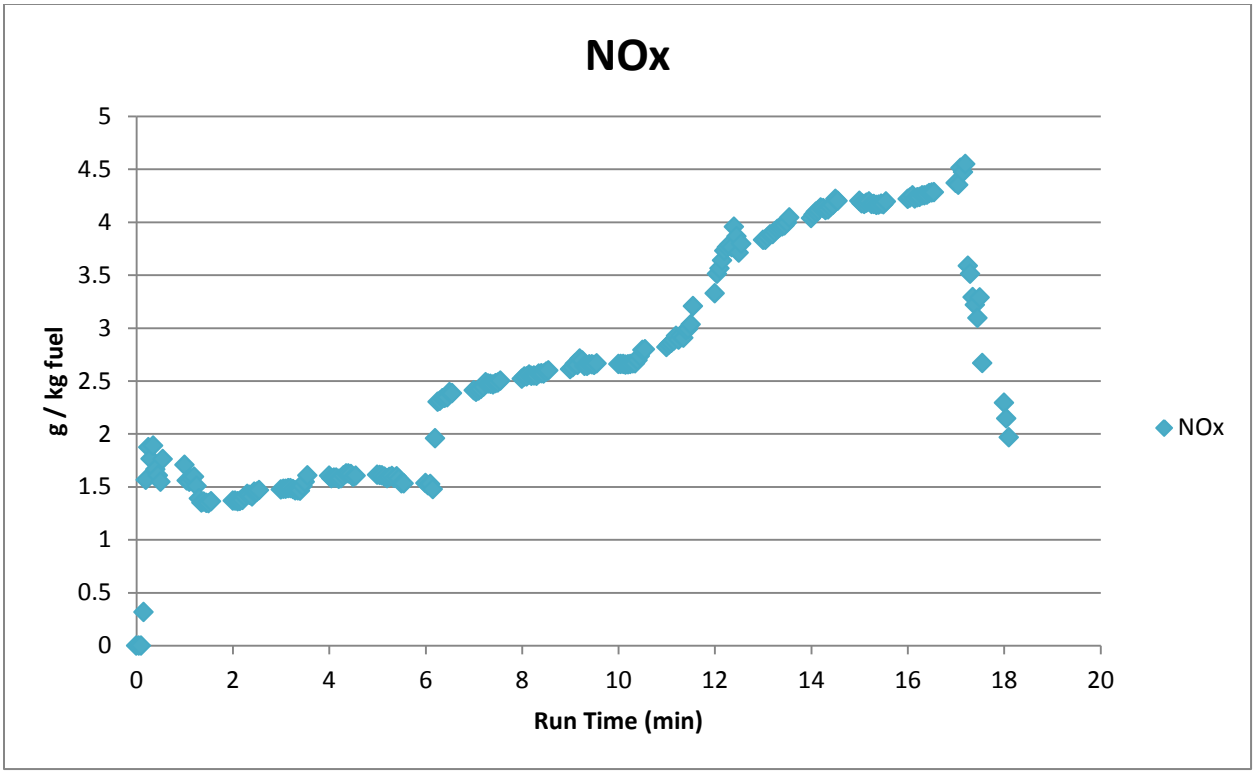

CO2
Instantaneous CO2 (g / kg fuel)
3200
3150
3100
3050
3000
2950
2900
2850
2800
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
CO2

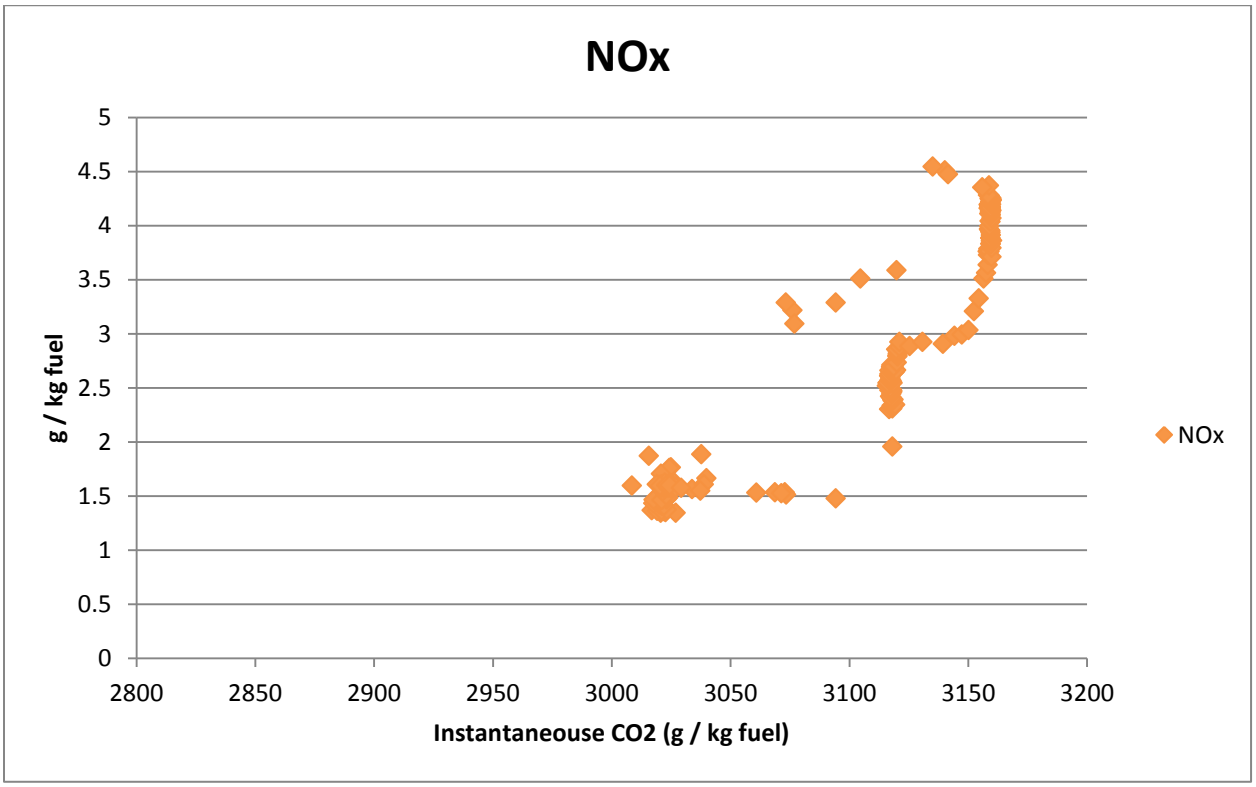

CO
g / kg fuel
90
80
70
60
50
40
30
20
10
0
2800
2850
2900
2950
3000
3050
3100
3150
3200
Instantaneous CO2 (g / kg fuel)
CO


NO
4
3.5
3
2.5
2
1.5
1
0.5
0
g / kg fuel
2800
2850
2900
2950
3000
3050
3100
3150
3200
Instantaneous CO2 (g / kg fuel)
NO


HC
40
35
30
25
20
15
10
5
0
g / kg fuel
2800
2850
2900
2950
3000
3050
3100
3150
3200
Instantaneous CO2 (g / kg fuel)
HC

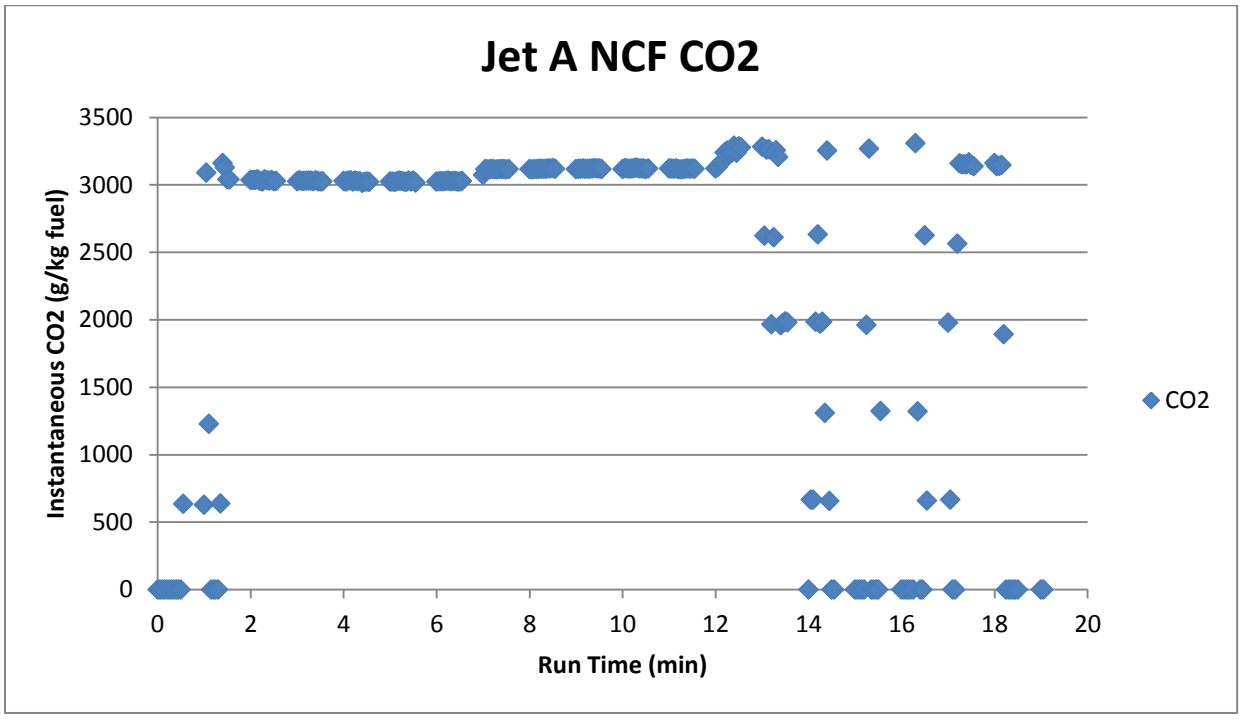
Salina2 Jet A Combined NOx 7/10/2012 PT6

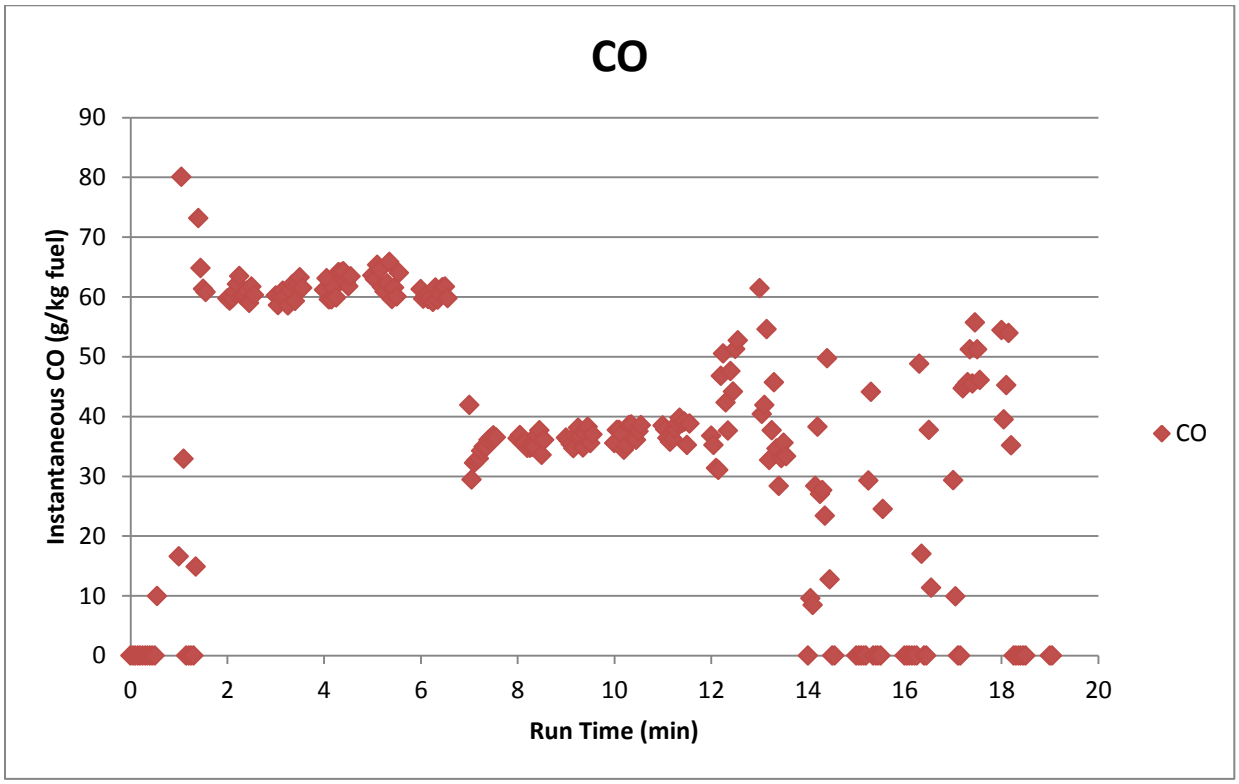


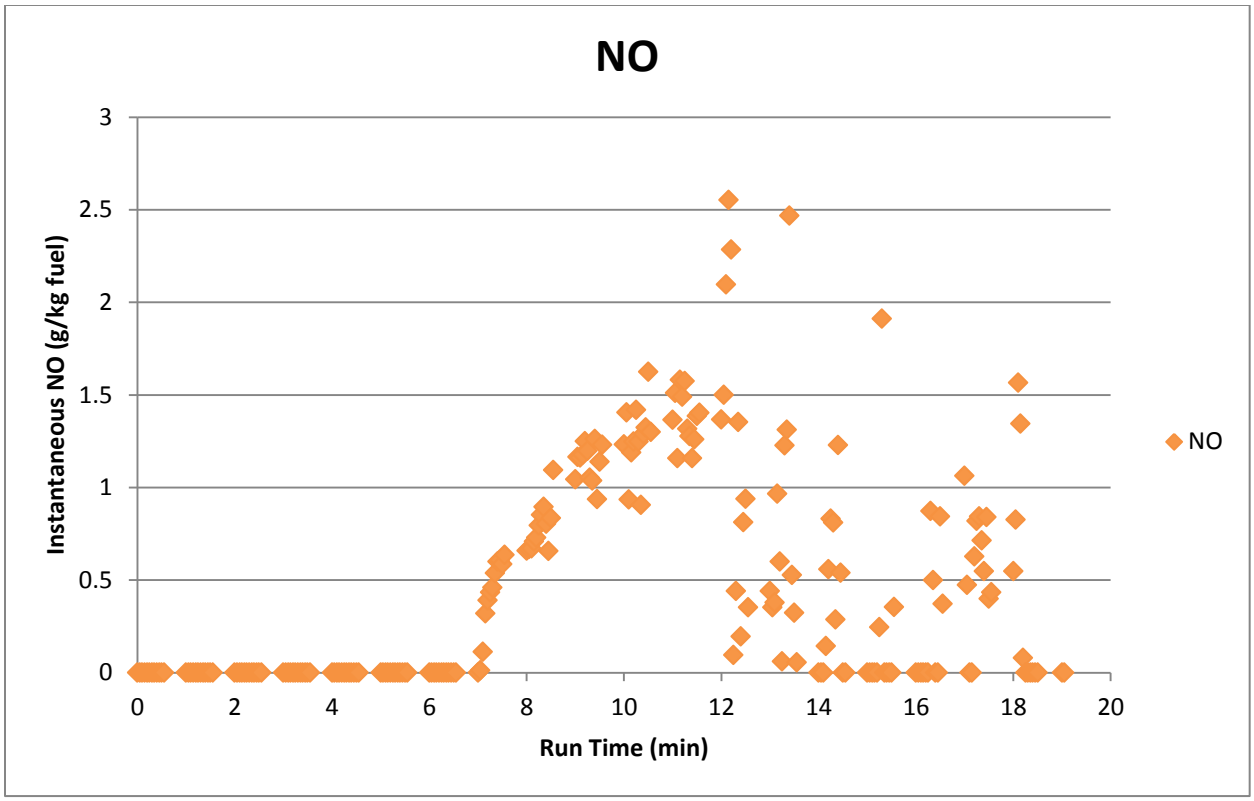


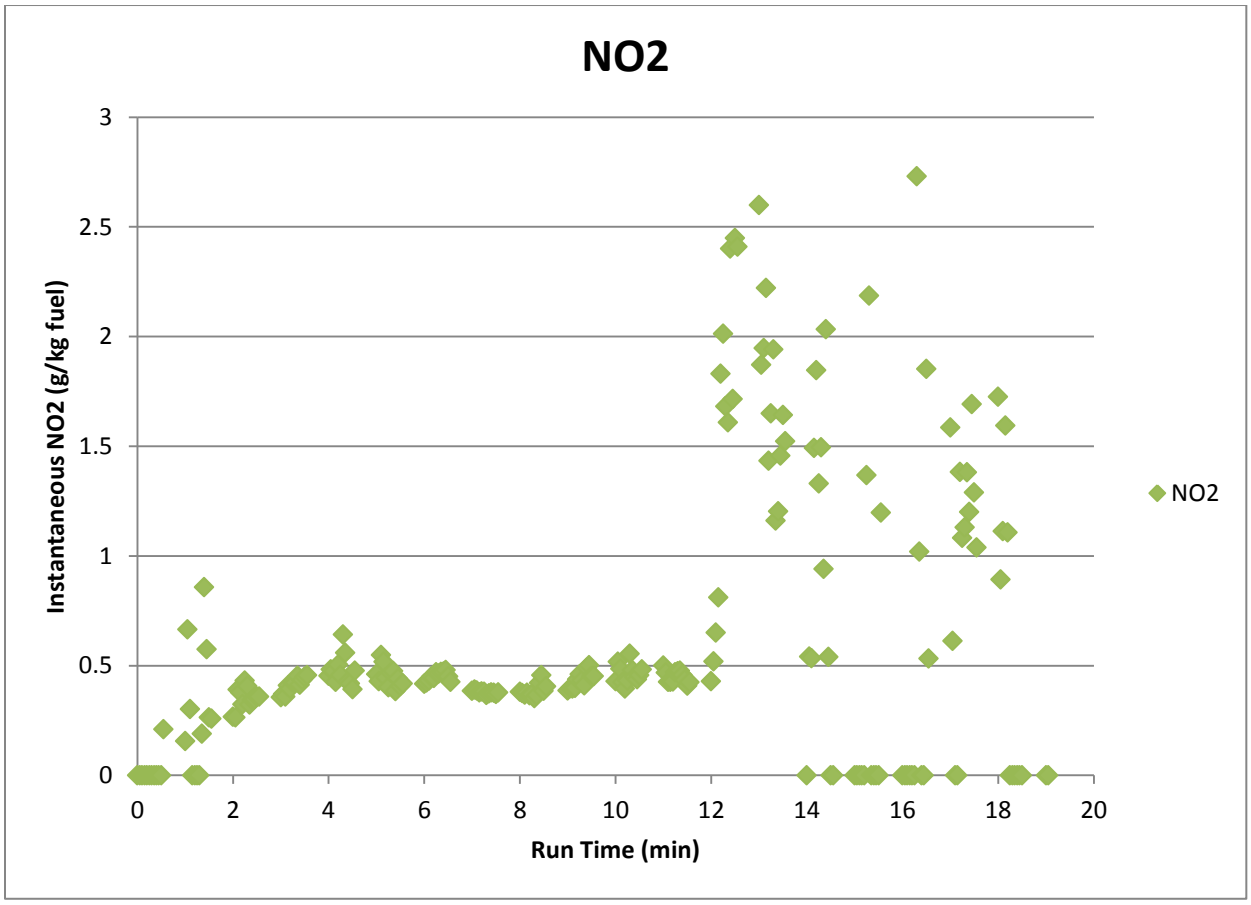
Appendix D: Results from 9/12/2012 Salina Sampling

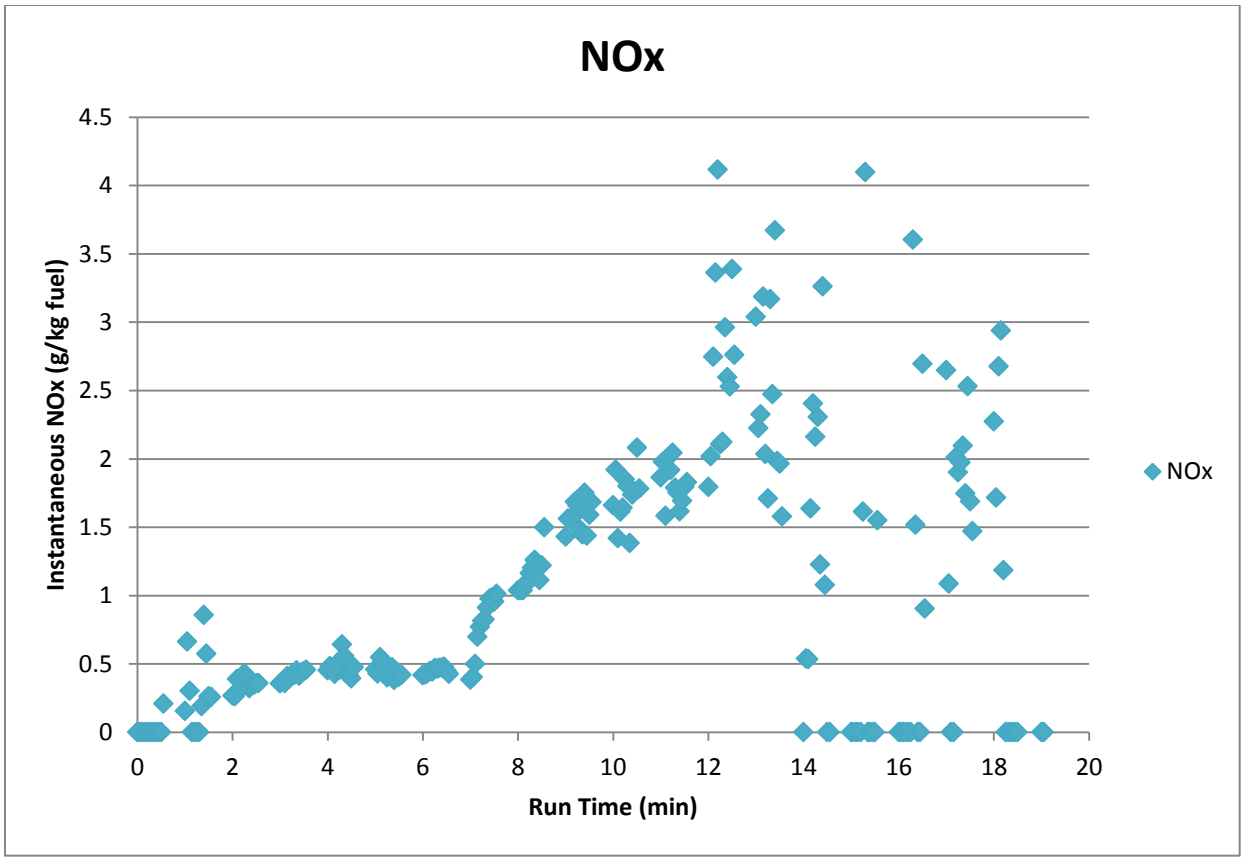
Salina3 Jet A NCF 9/12/2012 PT6

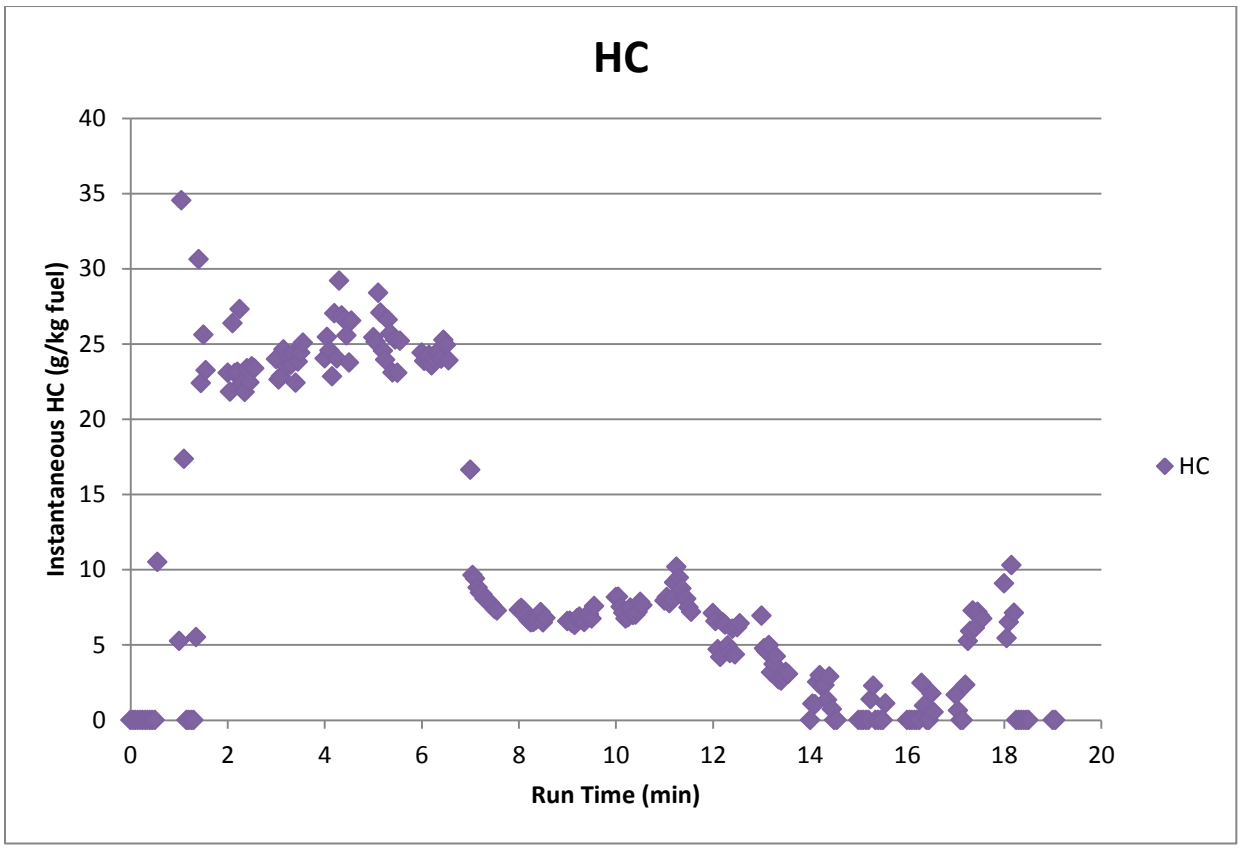


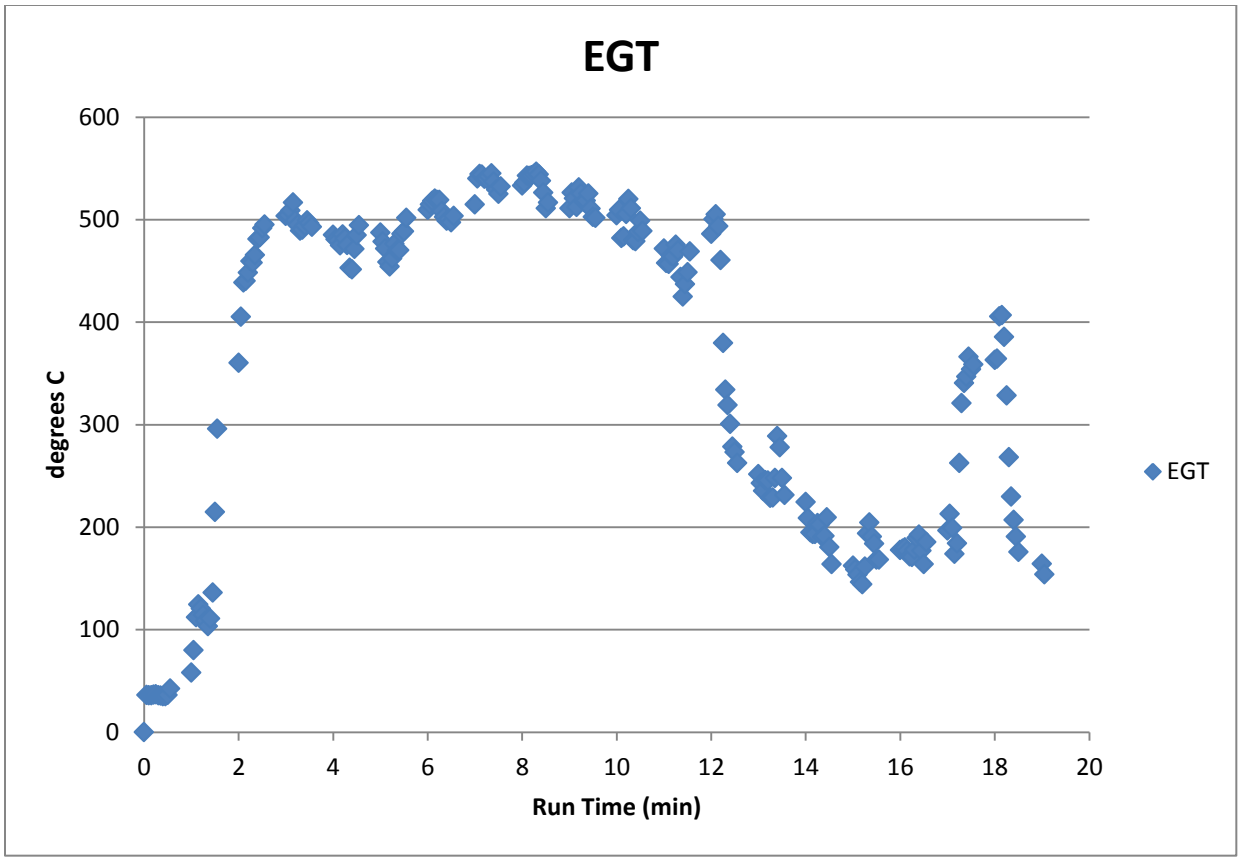


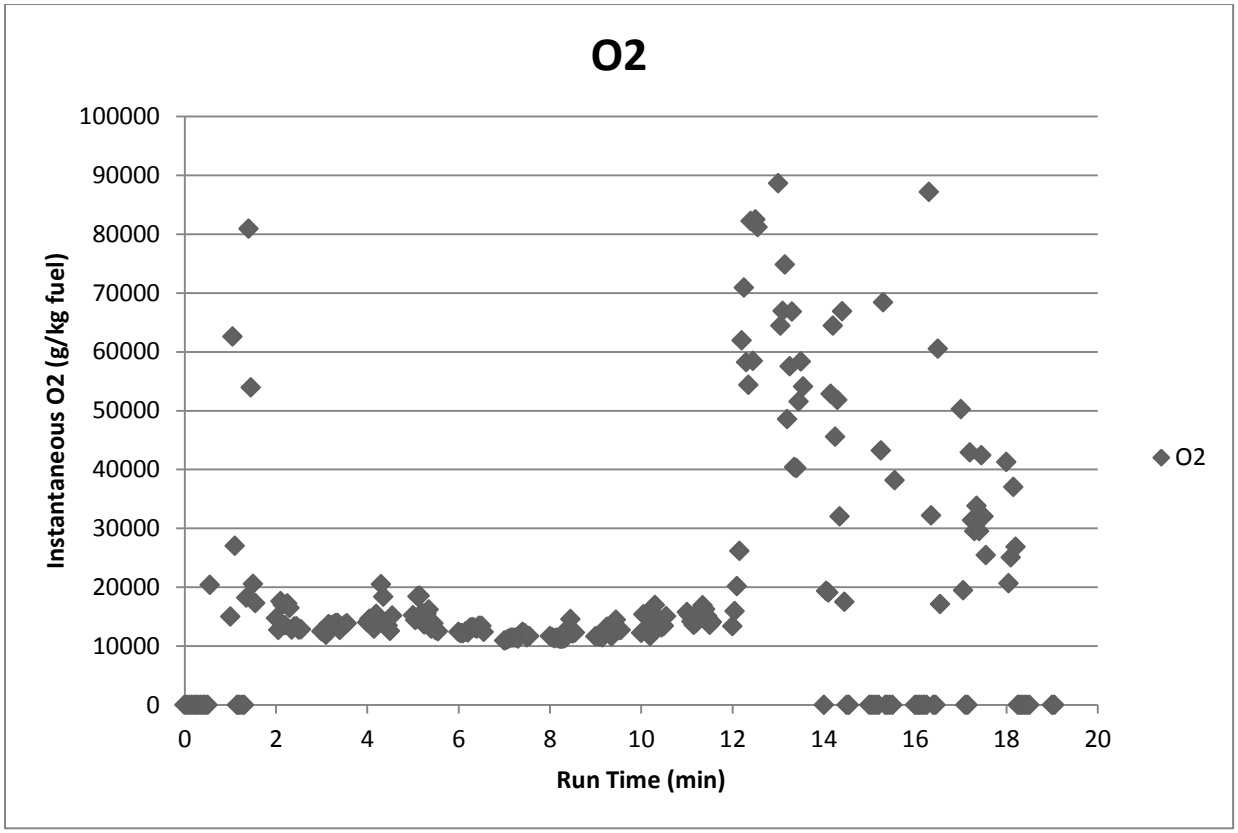

NO
Instantaneous NO (g/kg fuel)
3
2.5
2
1.5
1
0.5
0
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
NO

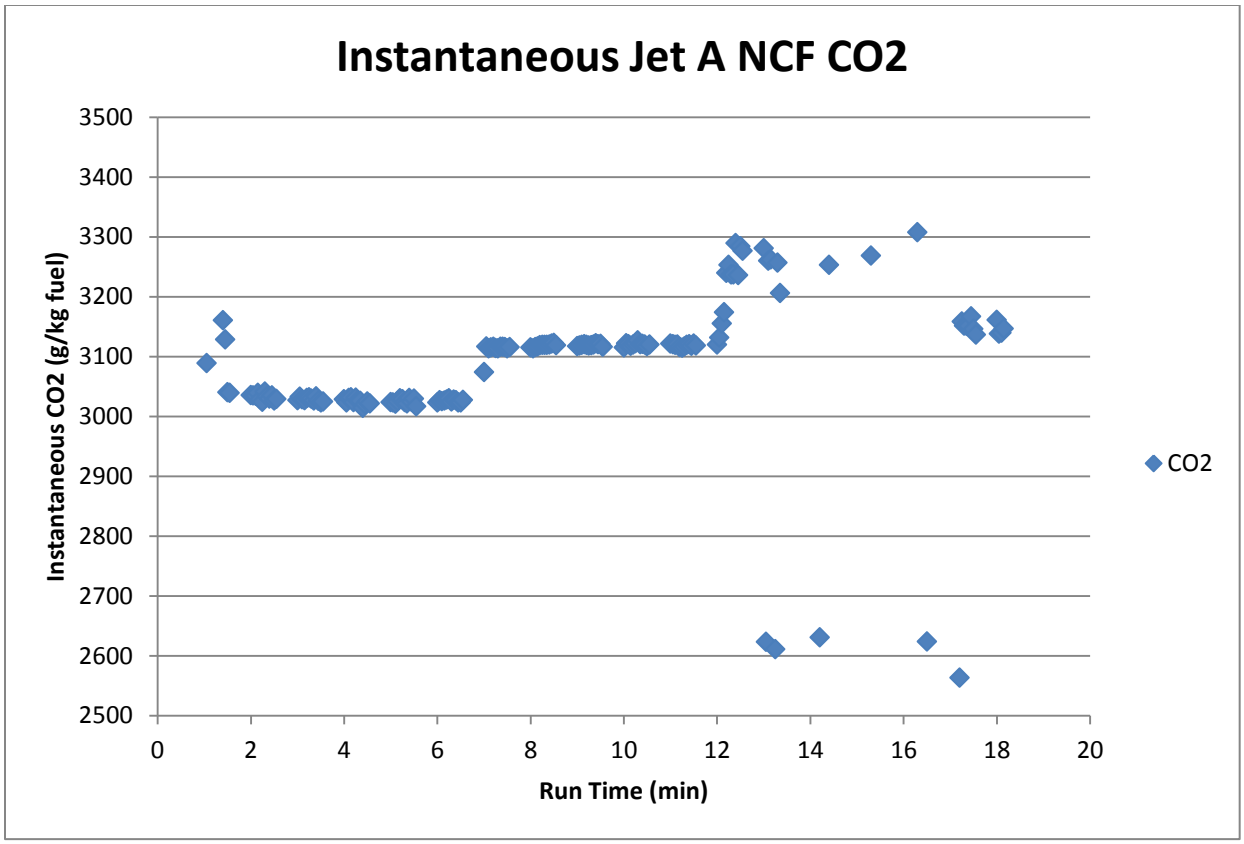

NO2
Instantaneous NO2 (g/kg fuel)
3
2.5
2
1.5
1
0.5
0
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
NO2

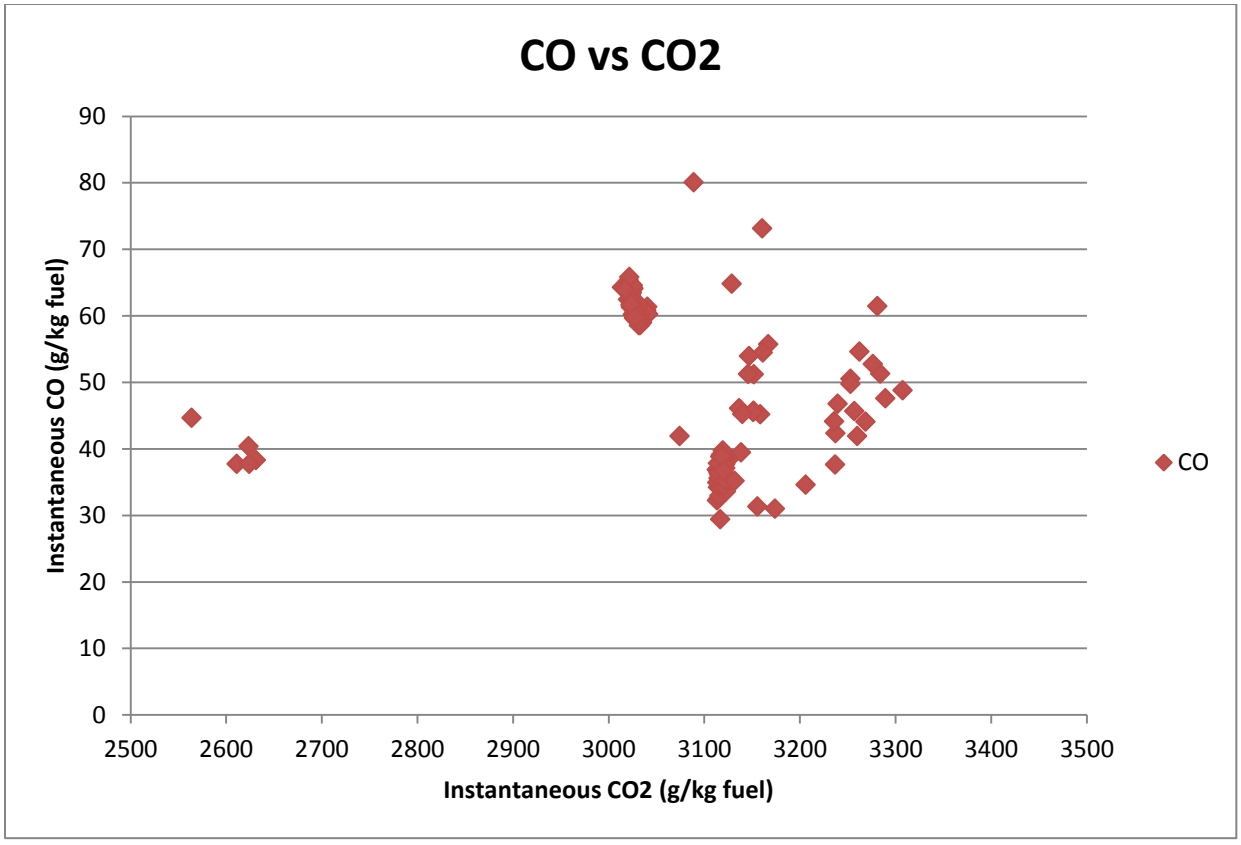

NOx
Instantaneous NOx (g/kg fuel)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
NOx

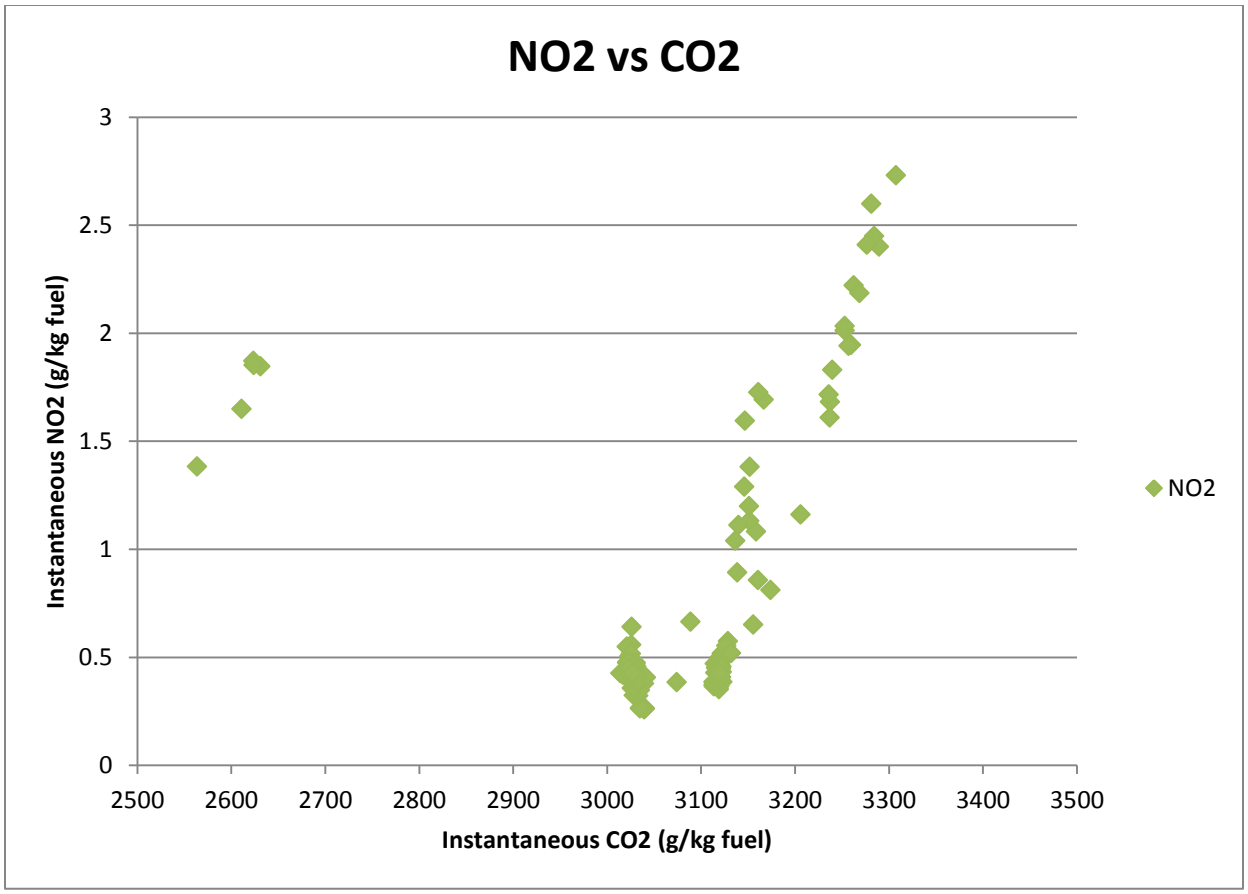

HC
Instantaneous HC (g/kg fuel)
40
35
30
25
20
15
10
5
0
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
HC

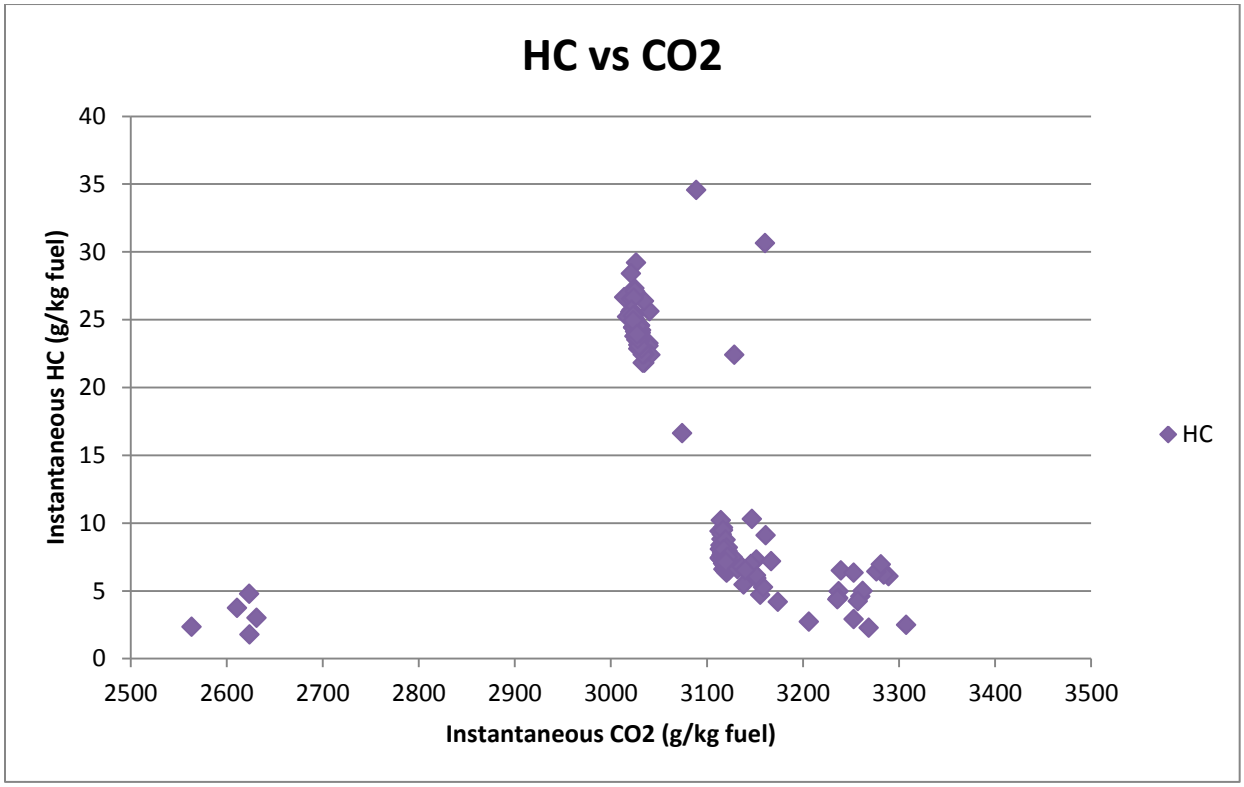

EGT
600
500
400
300
200
100
0
degrees C
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
EGT


O2
100000
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
Instantaneous O2 (g/kg fuel)
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
O2

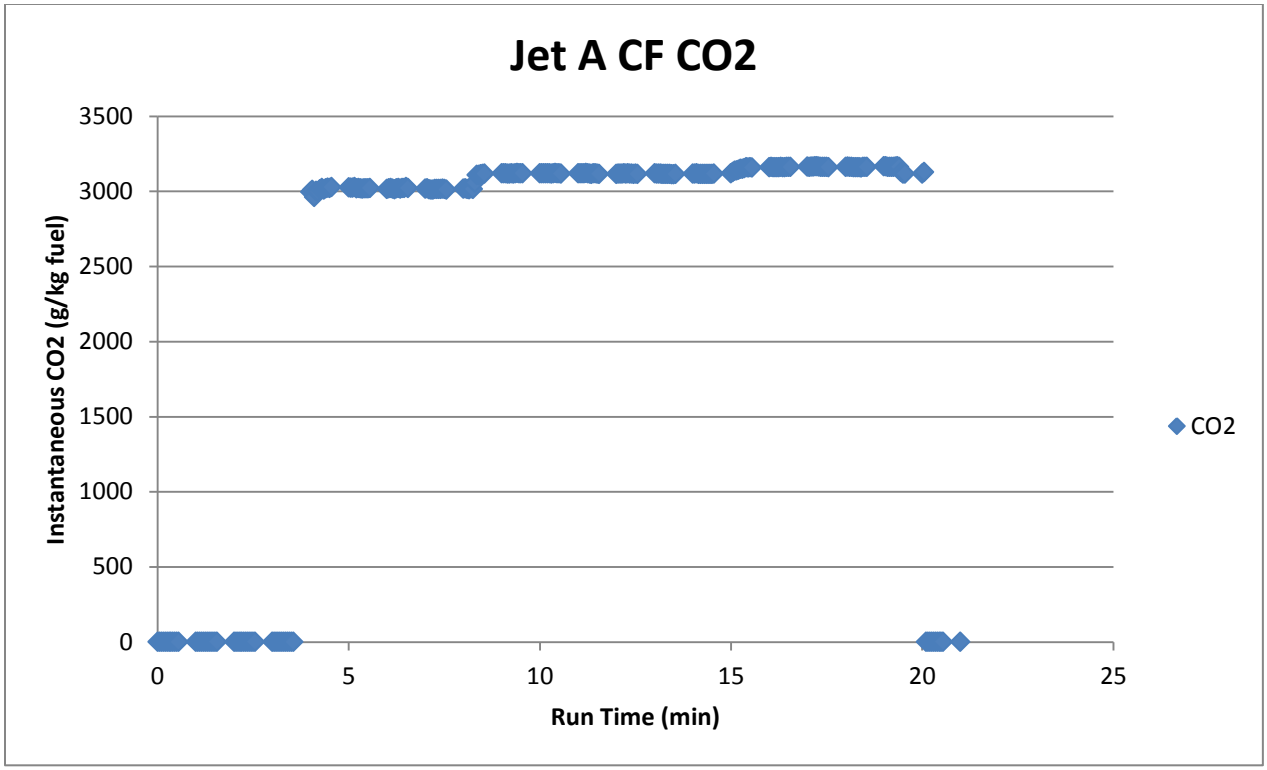

Instantaneous Jet A NCF CO2
Instantaneous CO2 (g/kg fuel)
3500
3400
3300
3200
3100
3000
2900
2800
2700
2600
2500
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
CO2

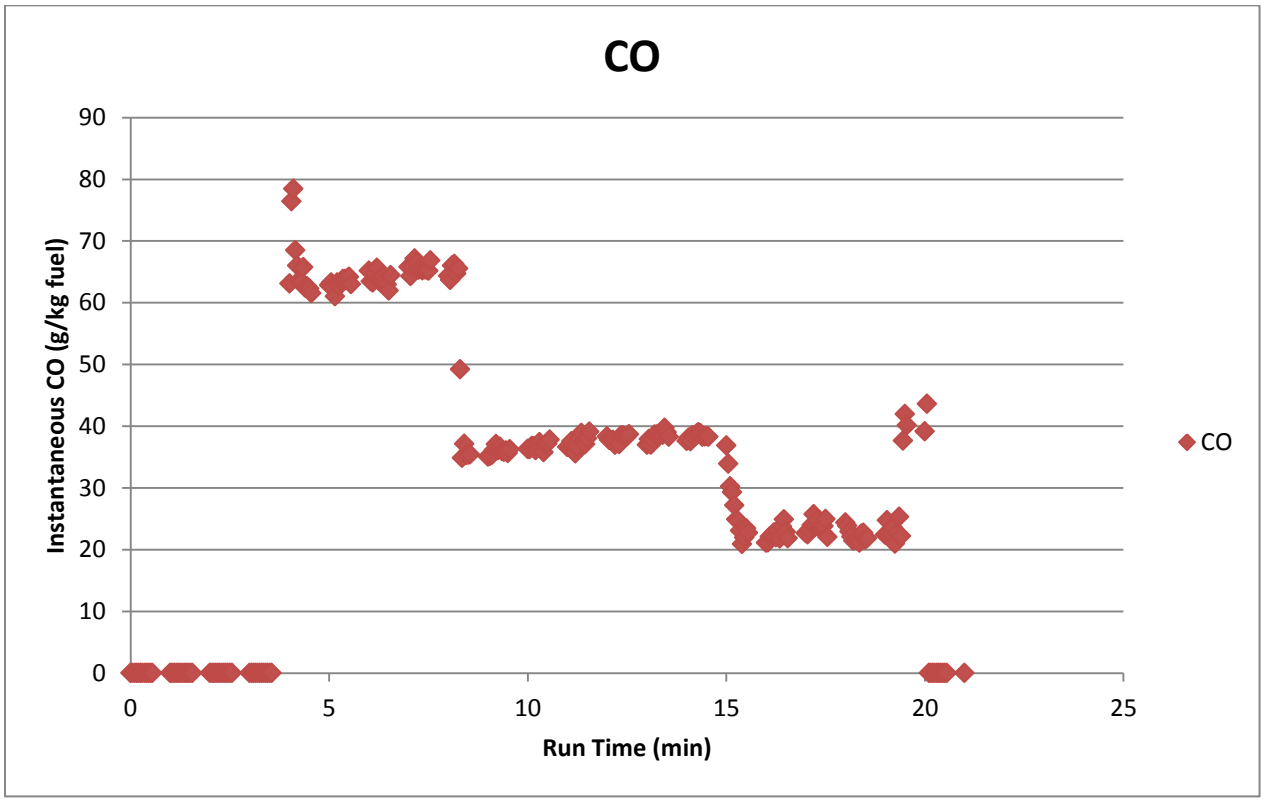

CO vs CO2
Instantaneous CO (g/kg fuel)
90
80
70
60
50
40
30
20
10
0
2500
2600
2700
2800
2900
3000
3100
3200
3300
3400
3500
Instantaneous CO2 (g/kg fuel)
CO

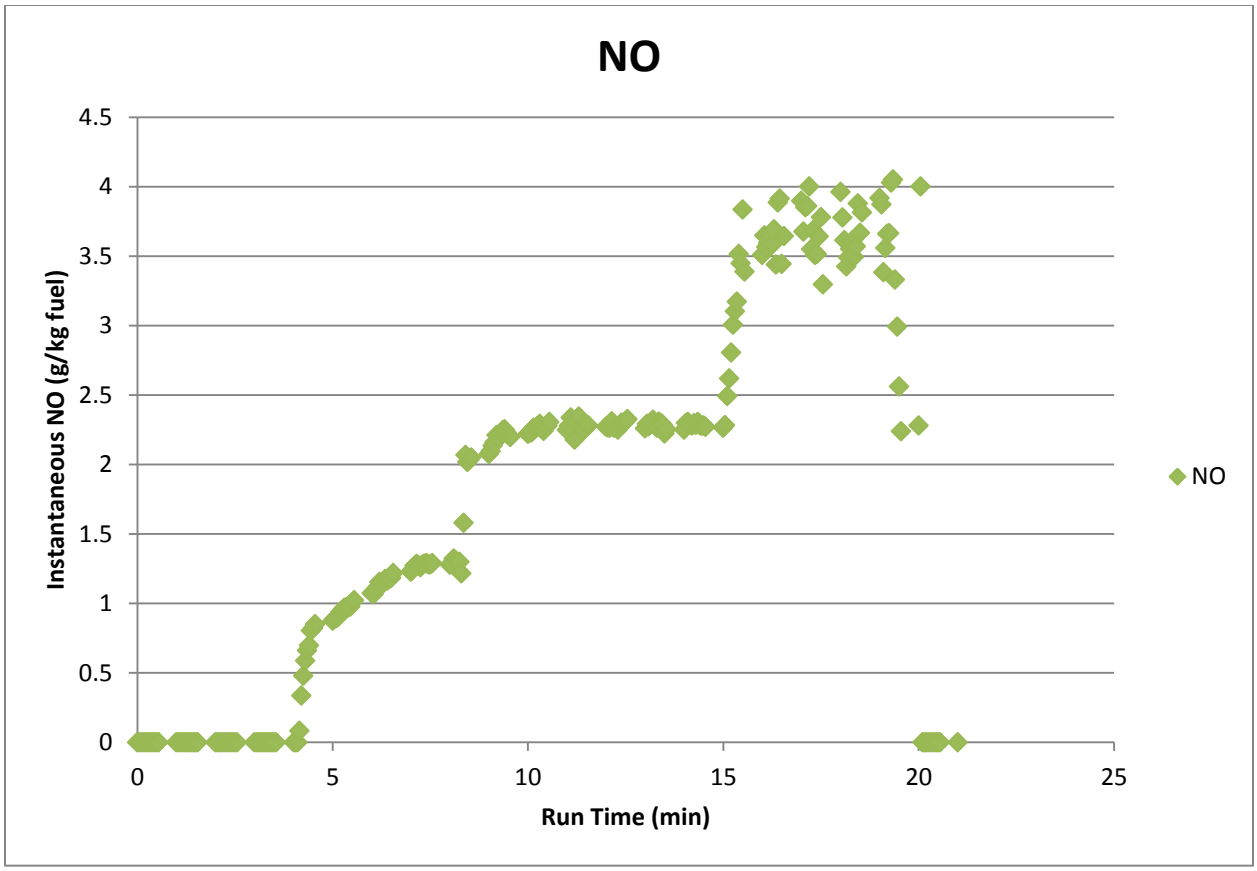

NO2 vs CO2
Instantaneous NO2 (g/kg fuel)
3
2.5
2
1.5
1
0.5
0
2500
2600
2700
2800
2900
3000
3100
3200
3300
3400
3500
Instantaneous CO2 (g/kg fuel)
NO2

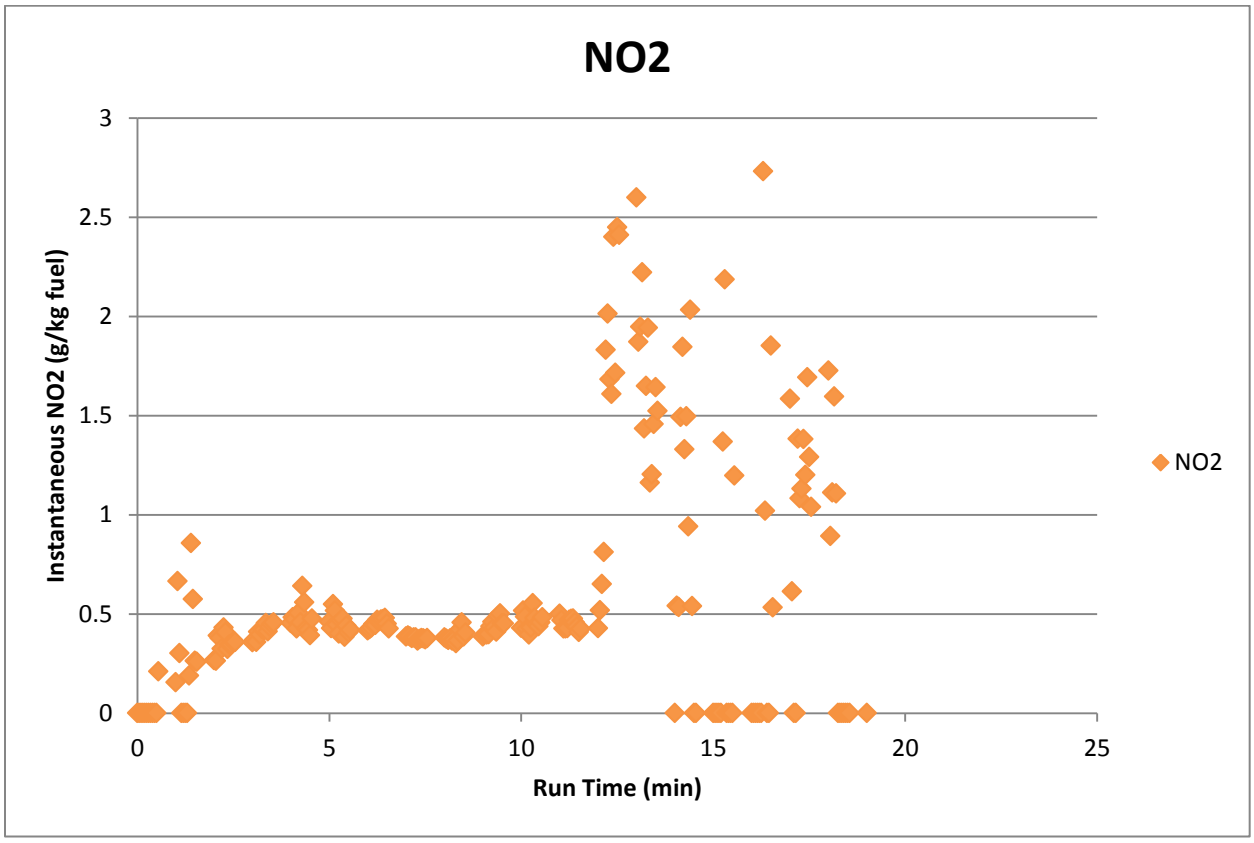

HC vs CO2
Instantaneous HC (g/kg fuel)
40
35
30
25
20
15
10
5
0
2500
2600
2700
2800
2900
3000
3100
3200
3300
3400
3500
Instantaneous CO2 (g/kg fuel)
HC

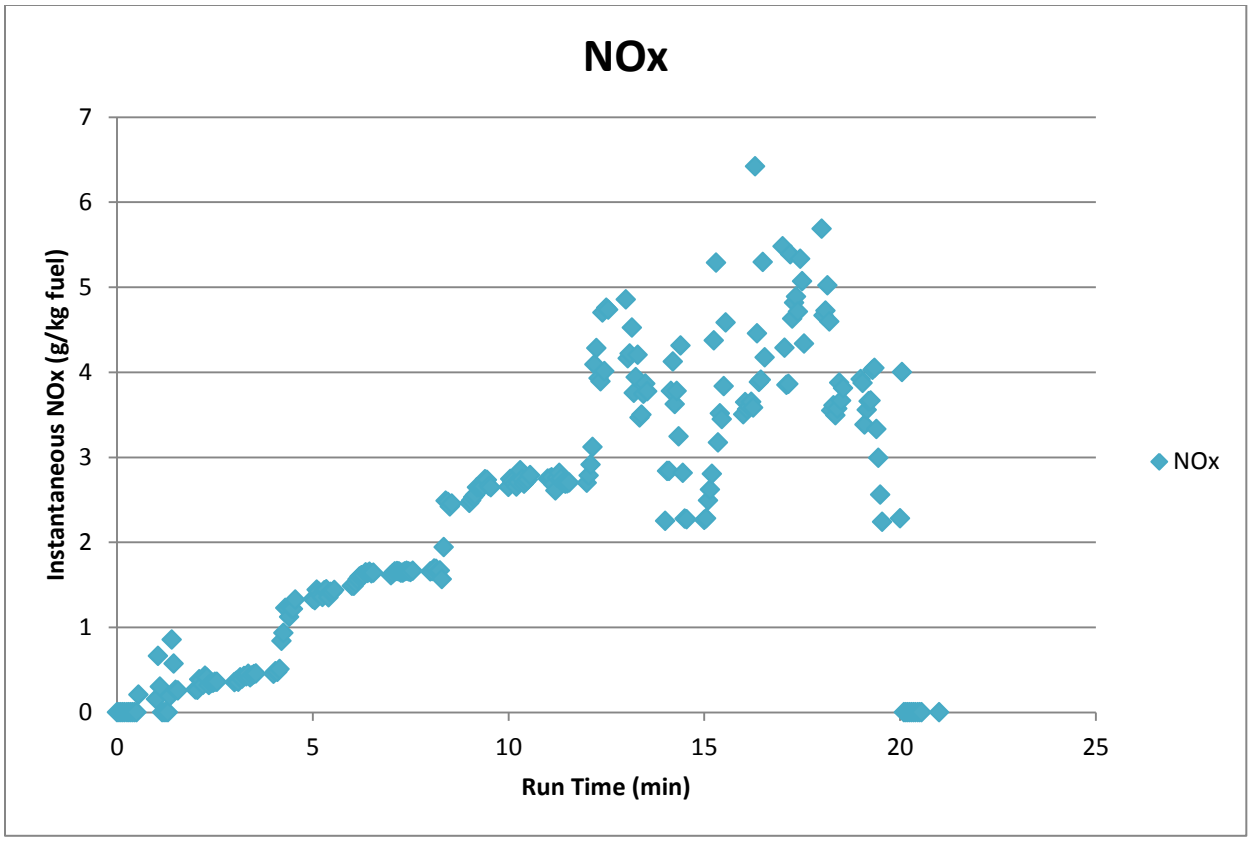
Salina3 Jet A CF 9/12/2012 PT6

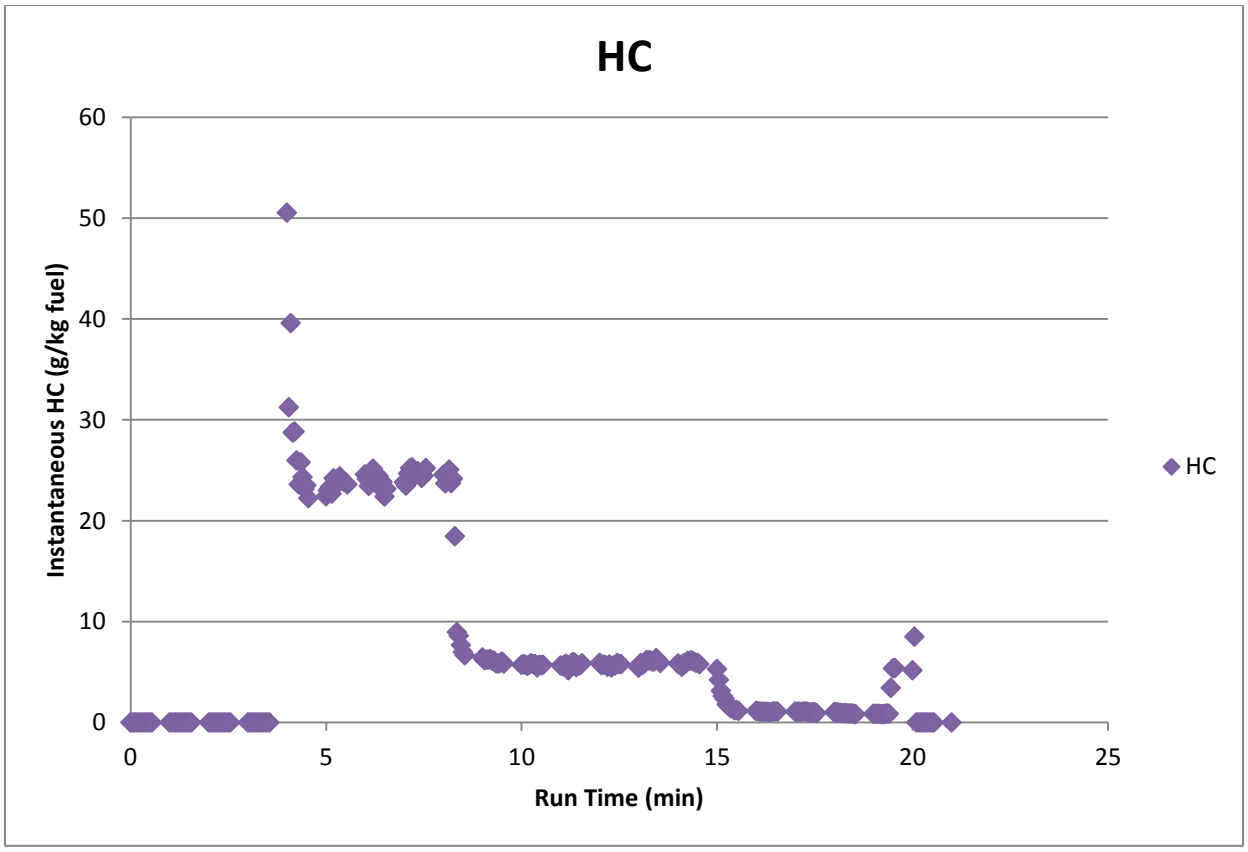


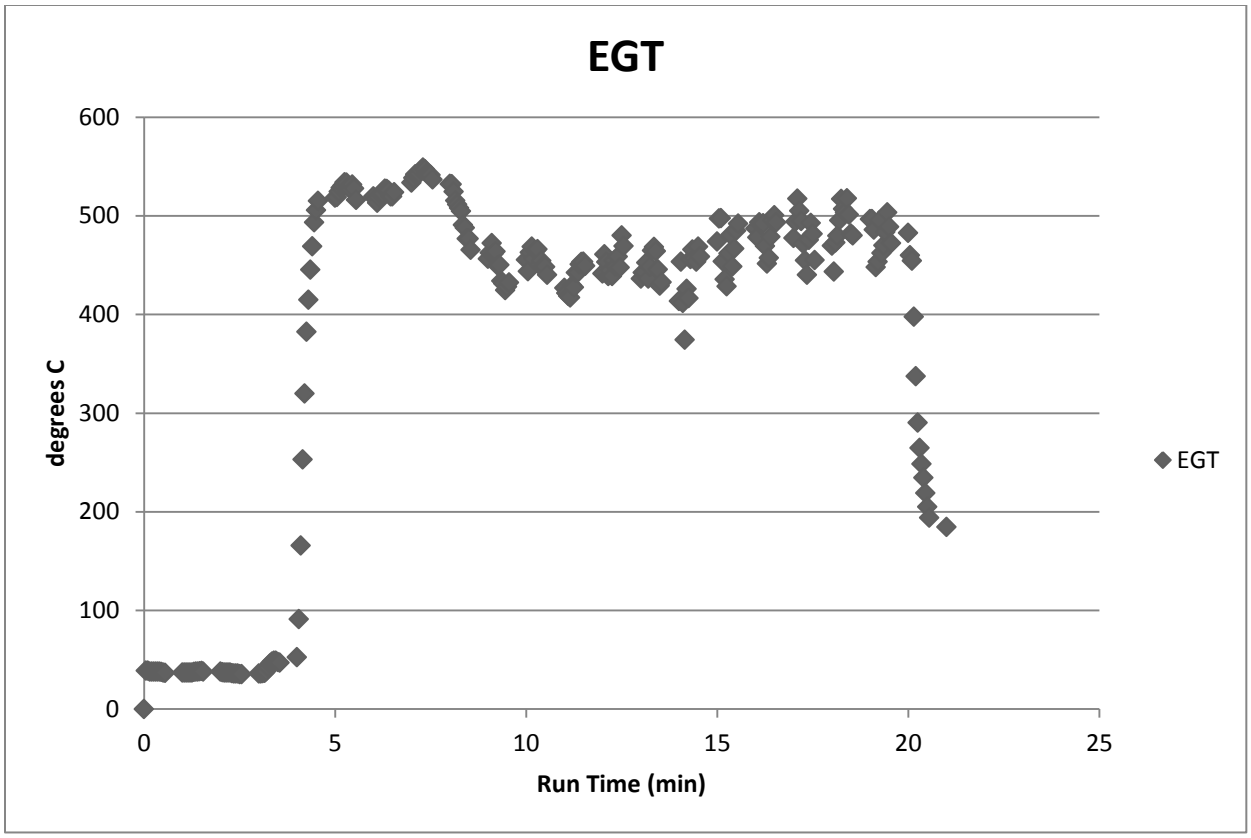


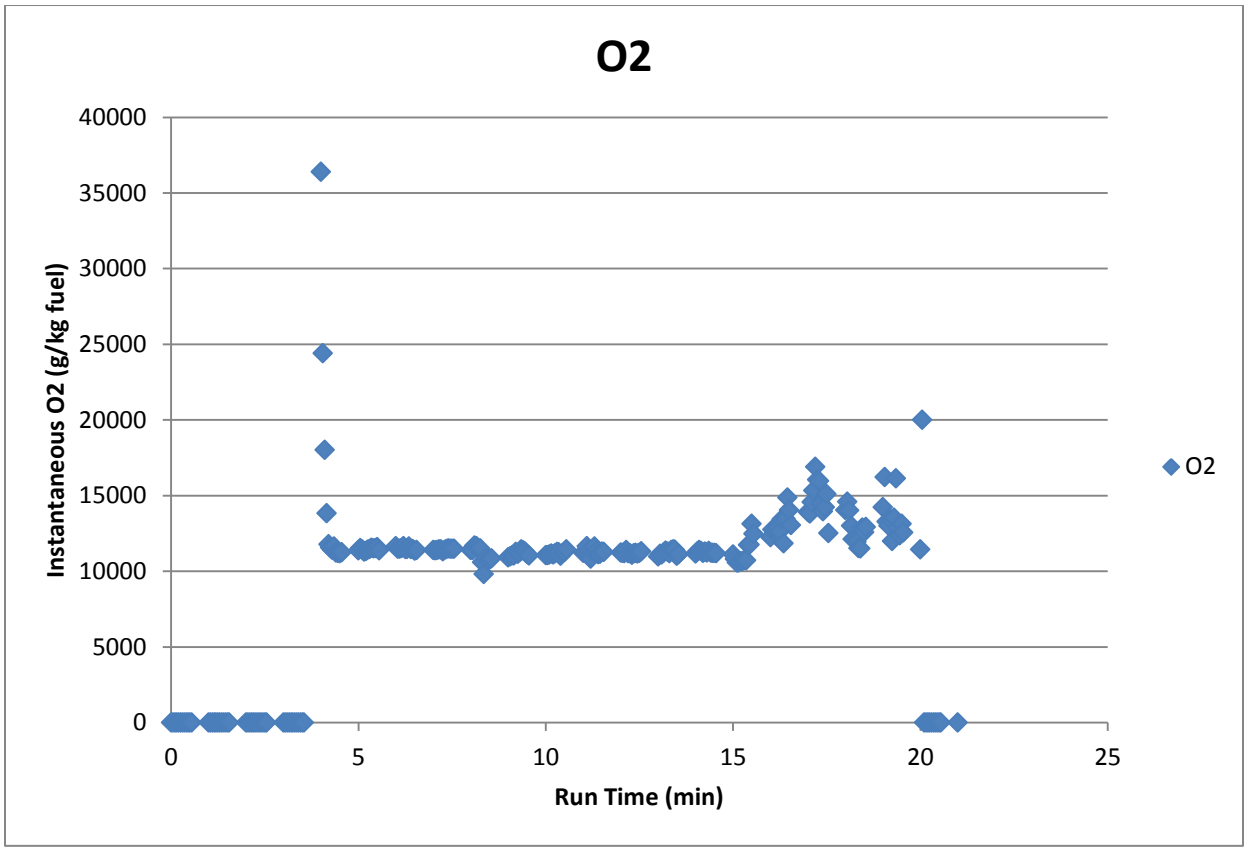

NO
Instantaneous NO (g/kg fuel)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
5
10
15
20
25
Run Time (min)
NO

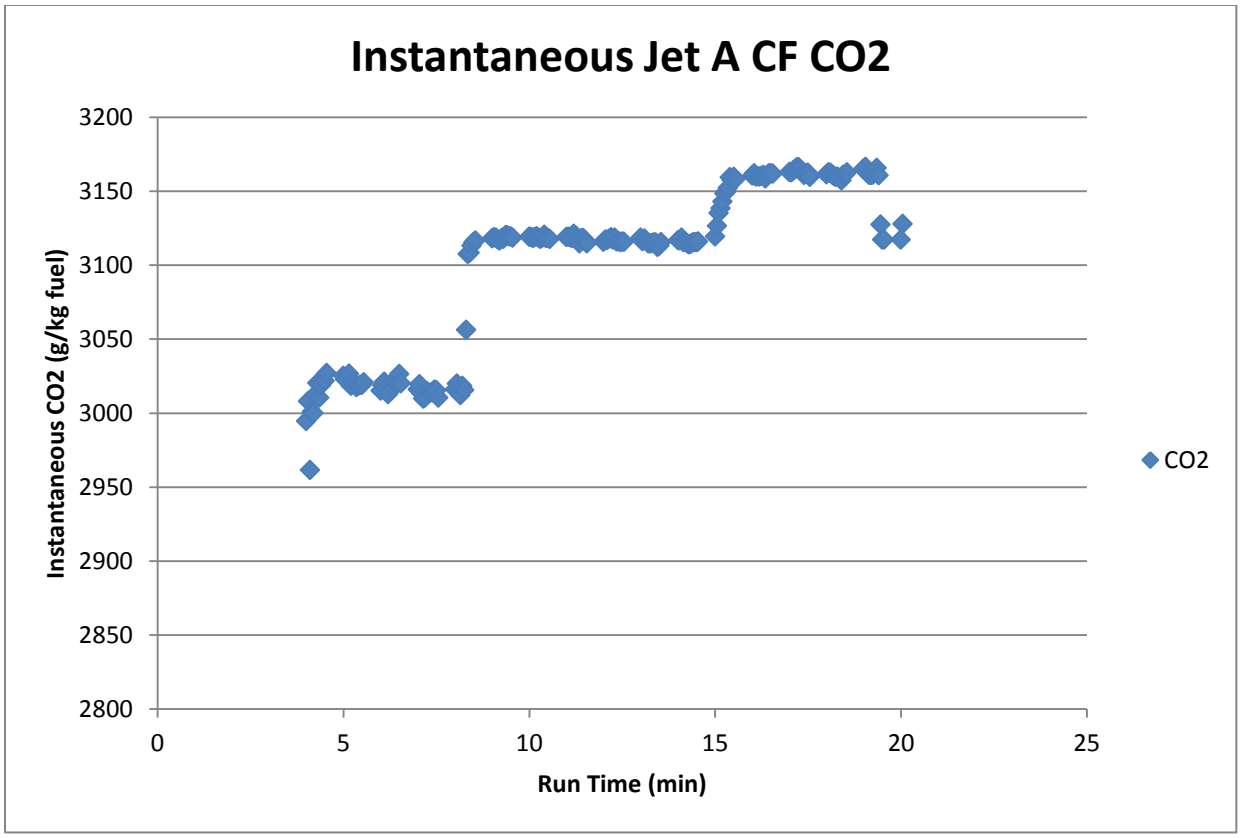

NO2
Instantaneous NO2 (g/kg fuel)
3
2.5
2
1.5
1
0.5
0
0
5
10
15
20
25
Run Time (min)
NO2

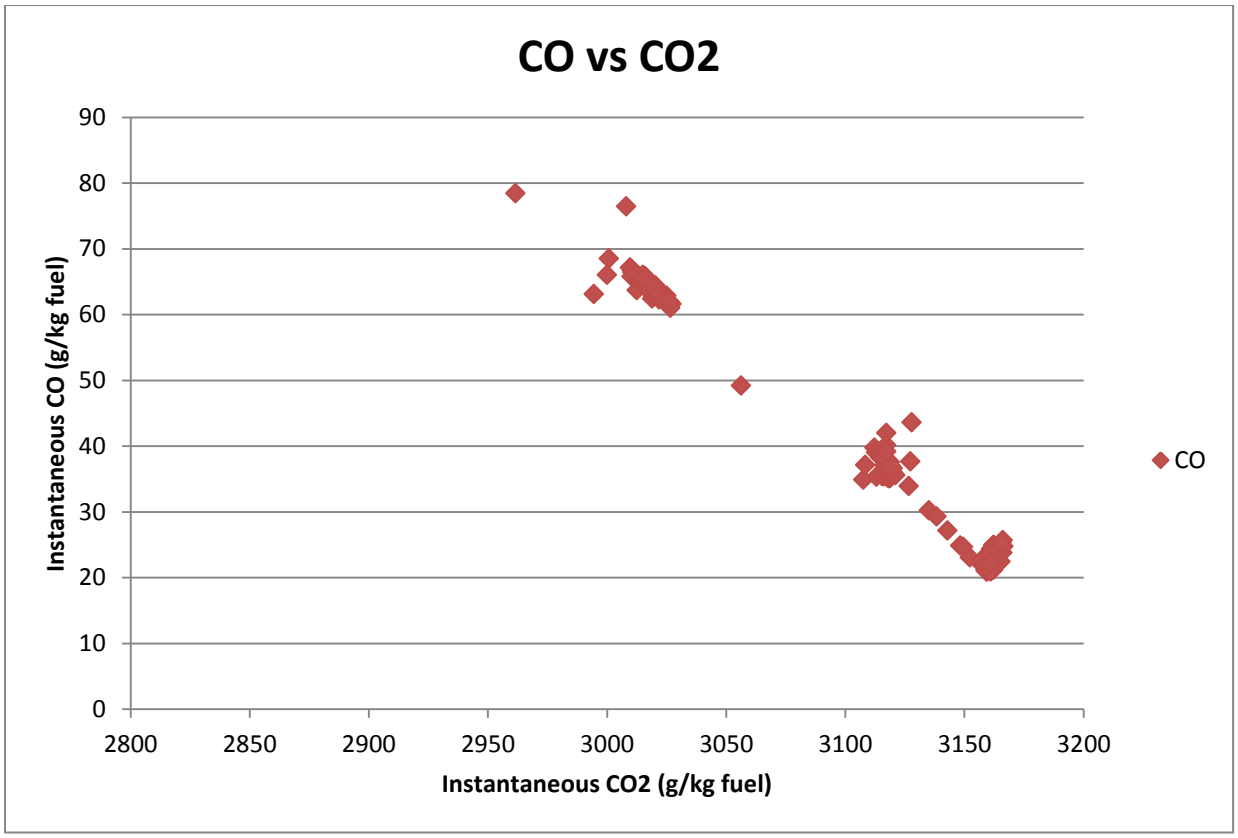

NOx
Instantaneous NOx (g/kg fuel)
0
1
2
3
4
5
6
7
0
5
10
15
20
25
Run Time (min)
NOx

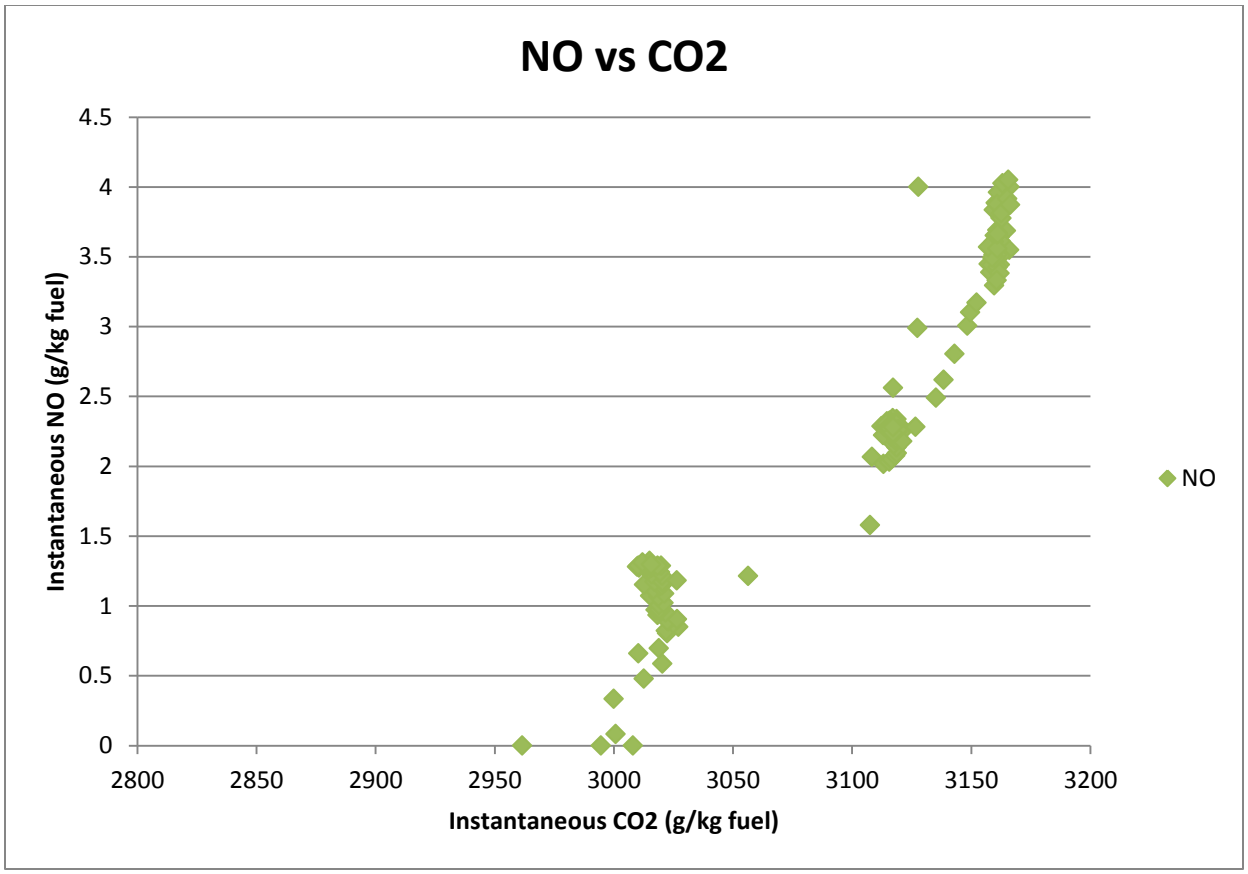

HC
Instantaneous HC (g/kg fuel)
0
10
20
30
40
50
60
0
5
10
15
20
25
Run Time (min)
HC

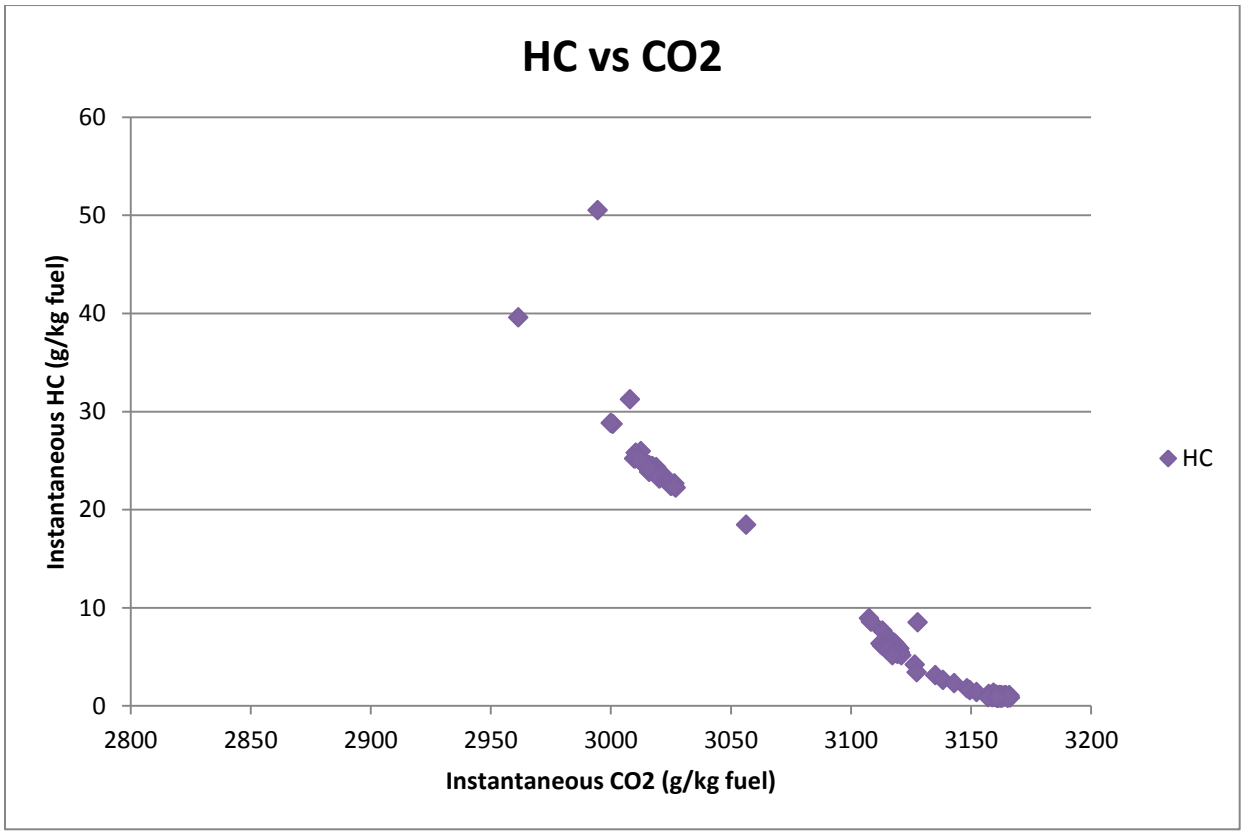

EGT
600
500
400
300
200
100
0
degrees C
0
5
10
15
20
25
Run Time (min)
EGT


O2
40000
35000
30000
25000
20000
15000
10000
5000
0
Instantaneous O2 (g/kg fuel)
0
5
10
15
20
25
Run Time (min)
O2

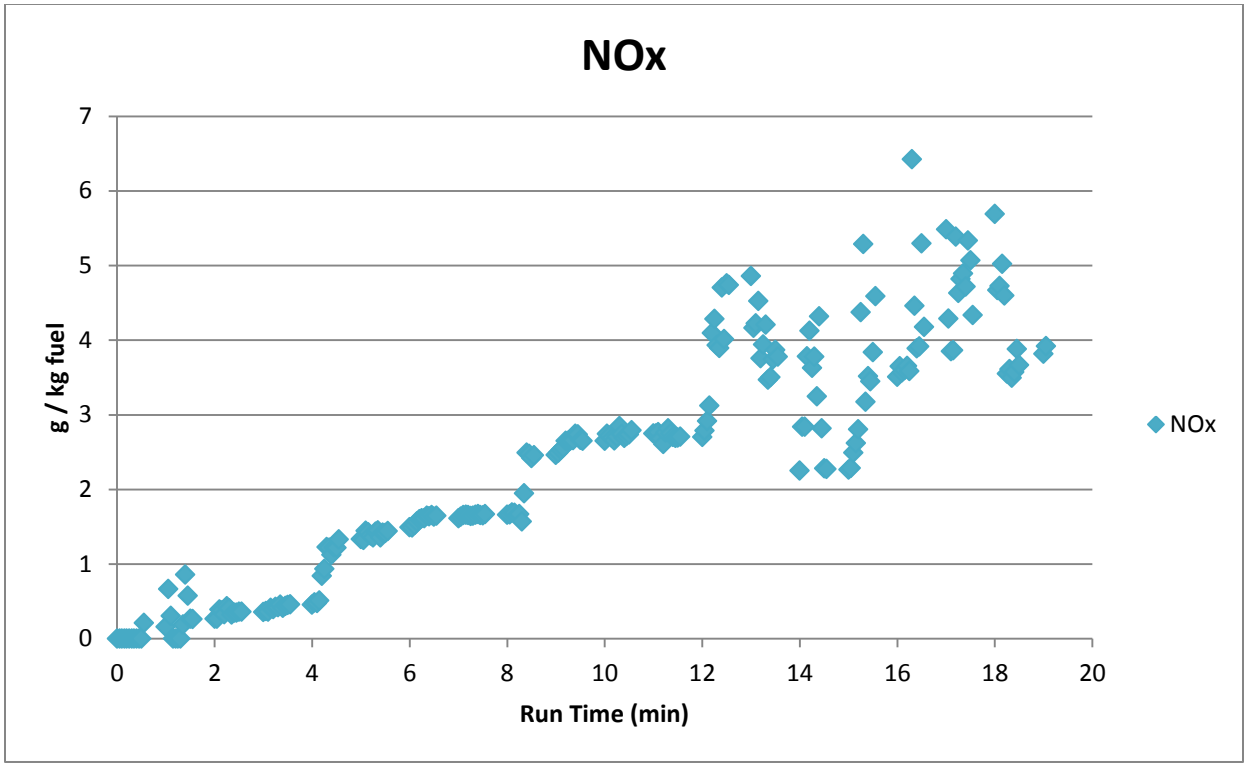

Instantaneous Jet A CF CO2
Instantaneous CO2 (g/kg fuel)
3200
3150
3100
3050
3000
2950
2900
2850
2800
0
5
10
15
20
25
Run Time (min)
CO2

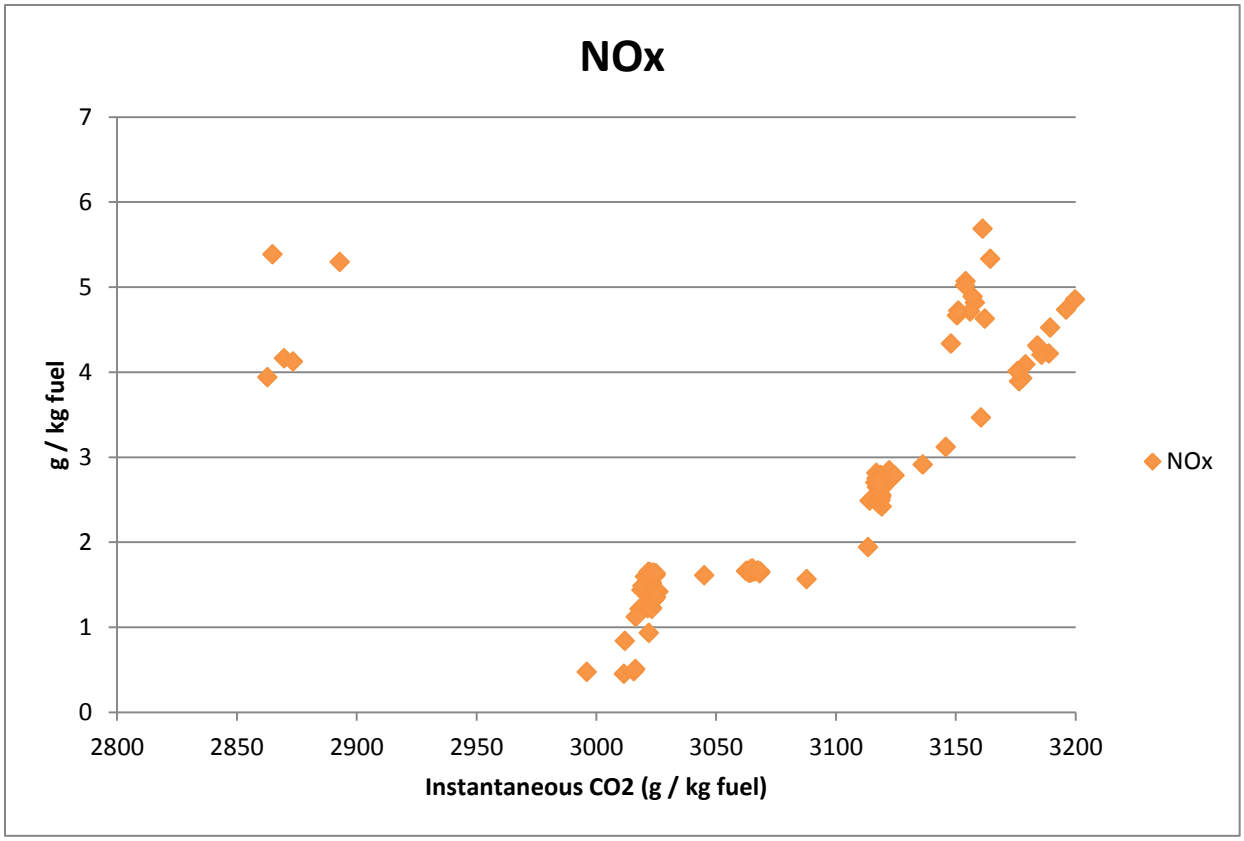

CO vs CO2
Instantaneous CO (g/kg fuel)
90
80
70
60
50
40
30
20
10
0
2800
2850
2900
2950
3000
3050
3100
3150
3200
Instantaneous CO2 (g/kg fuel)
CO


NO vs CO2
Instantaneous NO (g/kg fuel)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
2800
2850
2900
2950
3000
3050
3100
3150
3200
Instantaneous CO2 (g/kg fuel)
NO

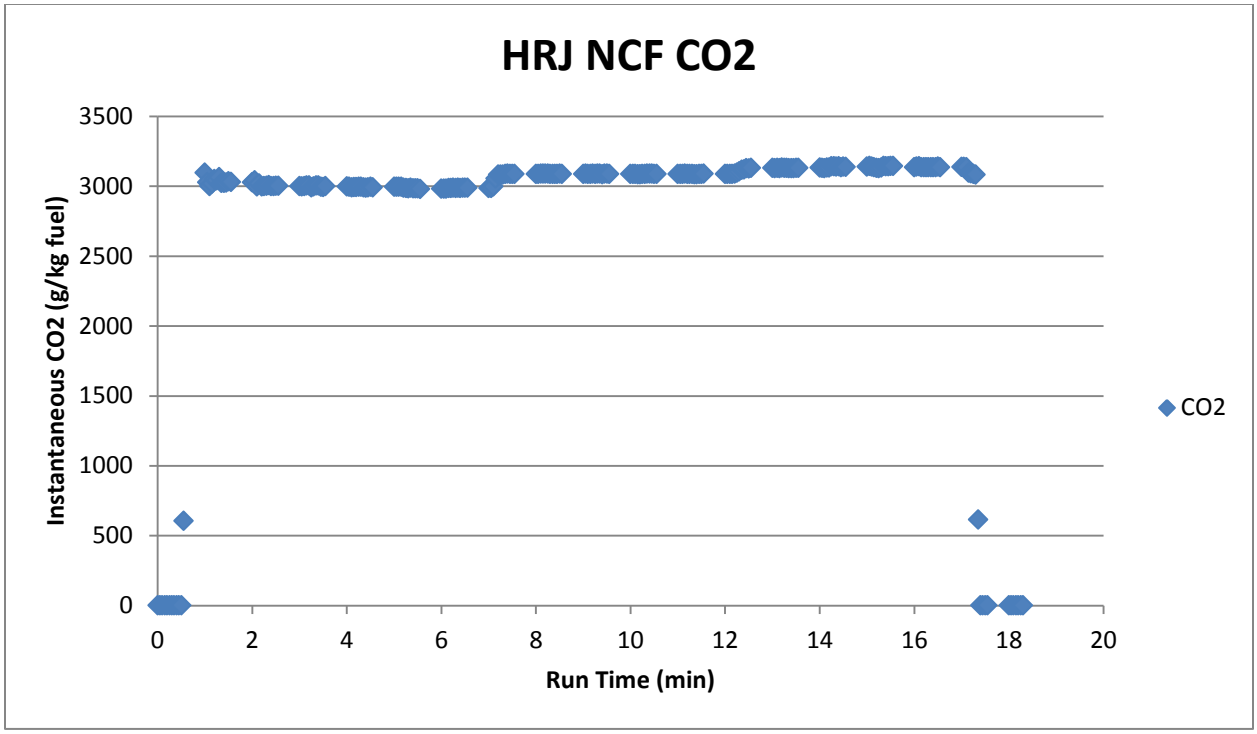

HC vs CO2
Instantaneous HC (g/kg fuel)
60
50
40
30
20
10
0
2800
2850
2900
2950
3000
3050
3100
3150
3200
Instantaneous CO2 (g/kg fuel)
HC

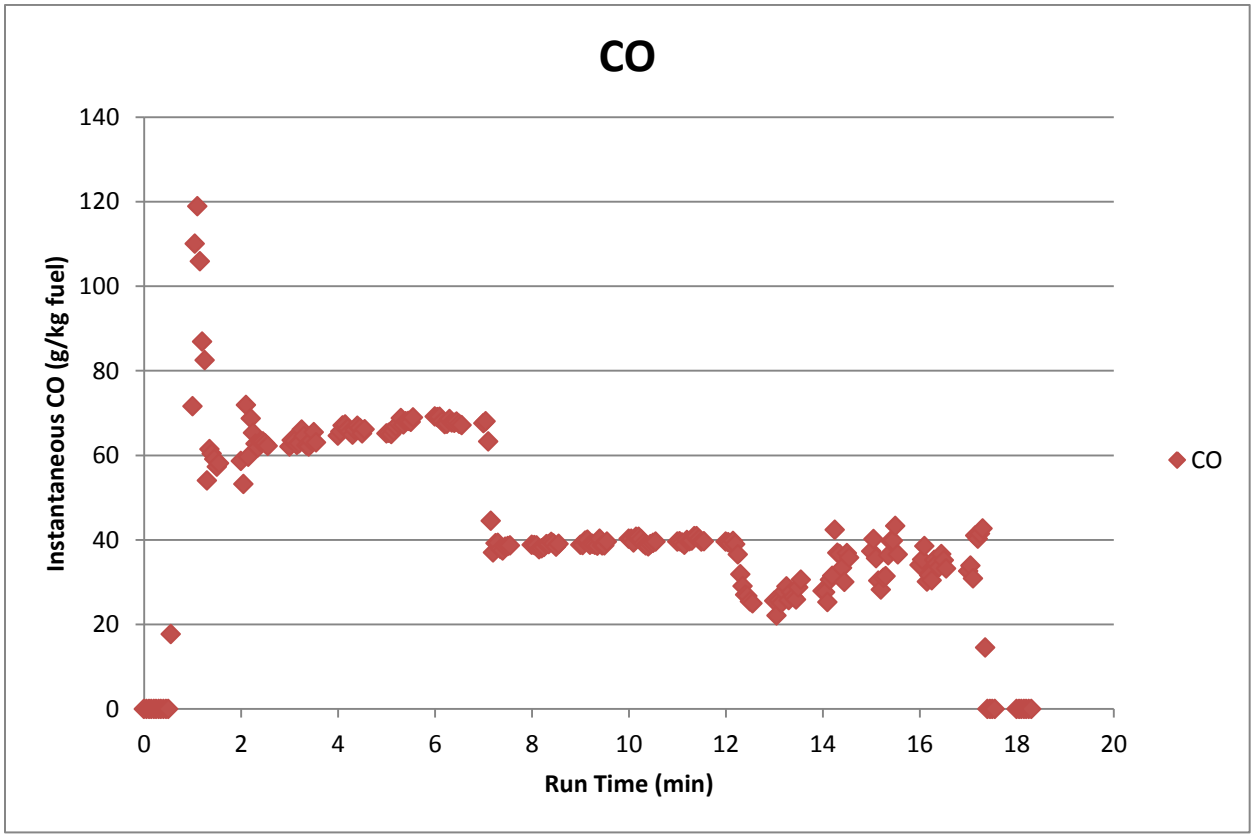
Salina3 Jet A Combined NOx 9/12/2012 PT6

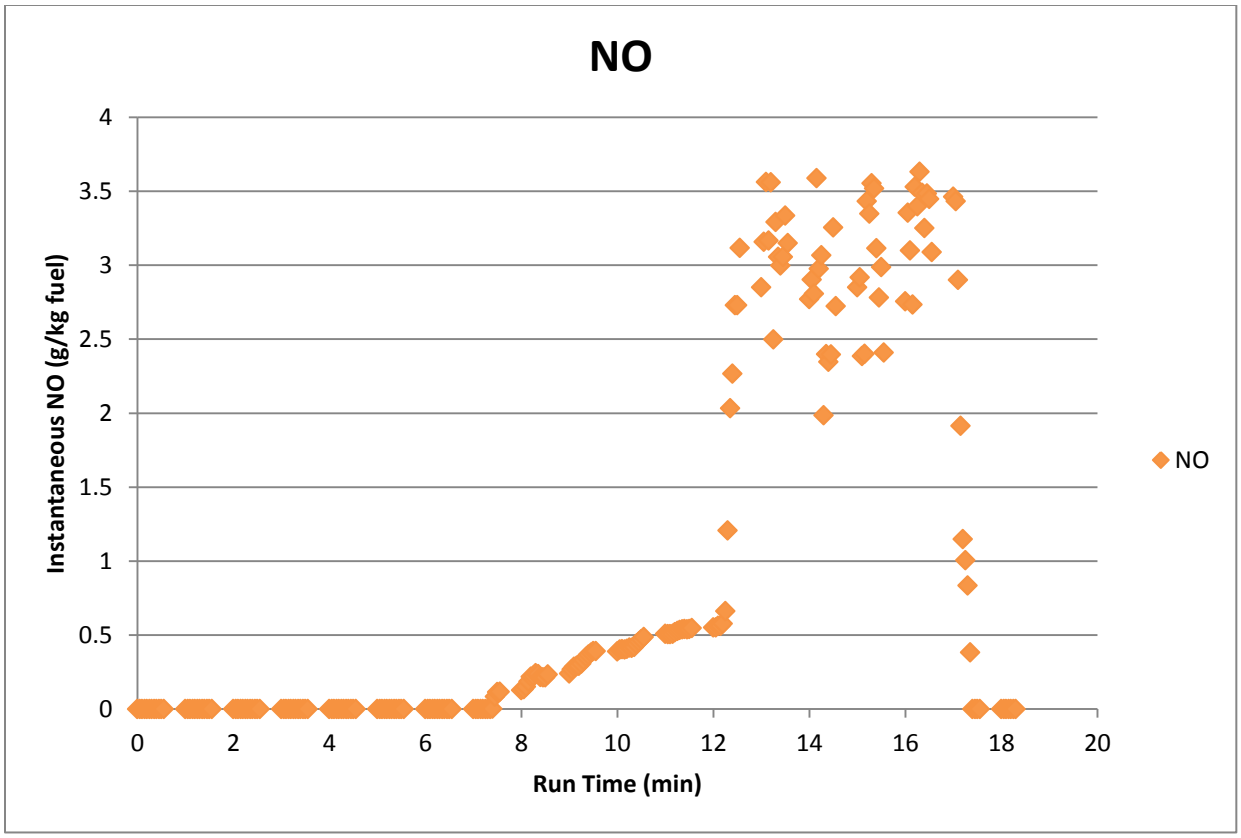


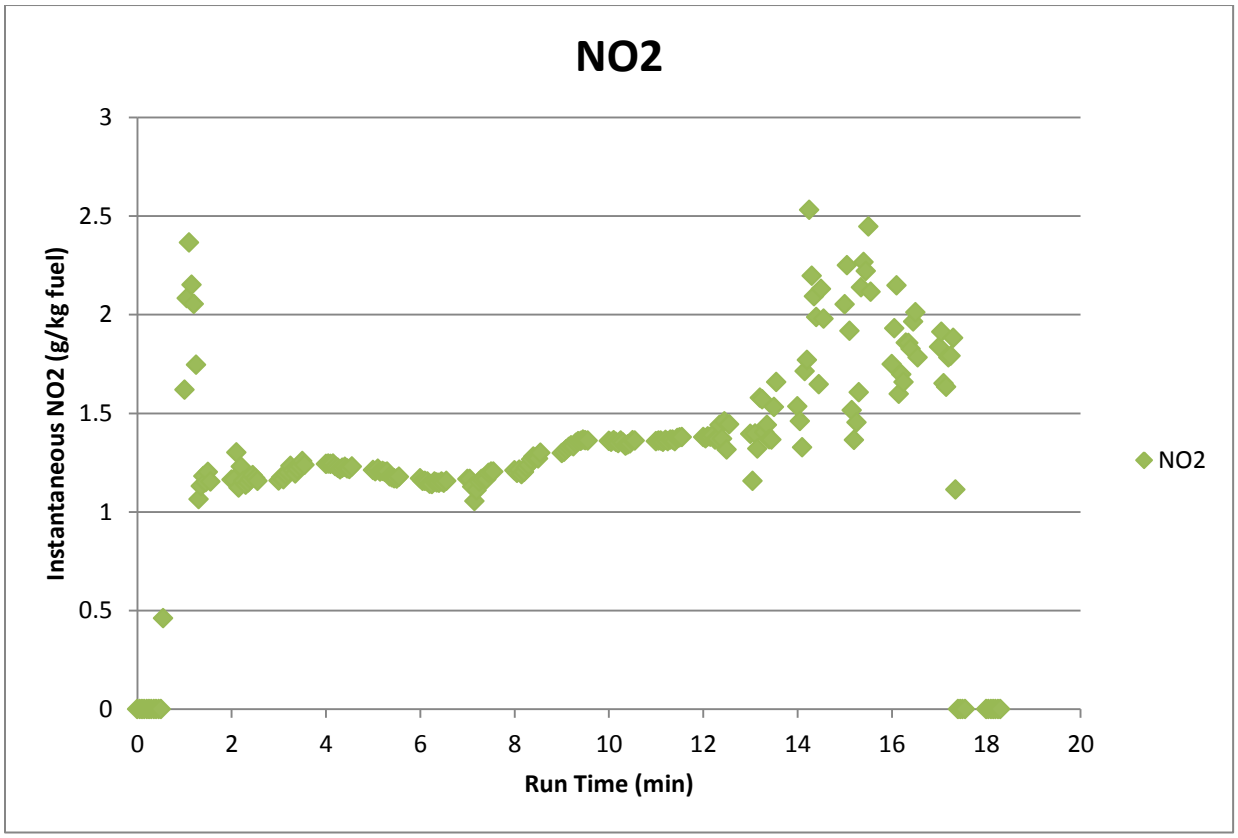


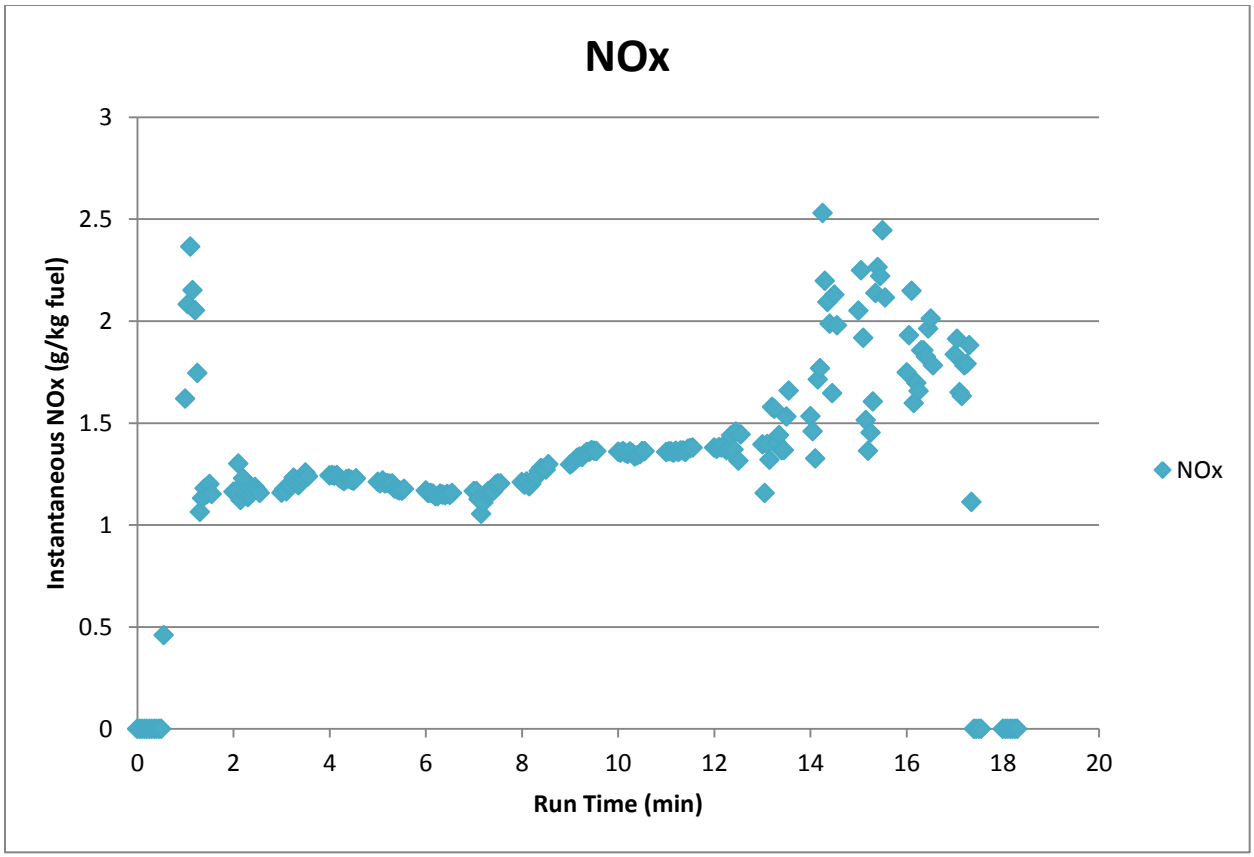
Salina3 HRJ NCF 9/12/2012 PT6

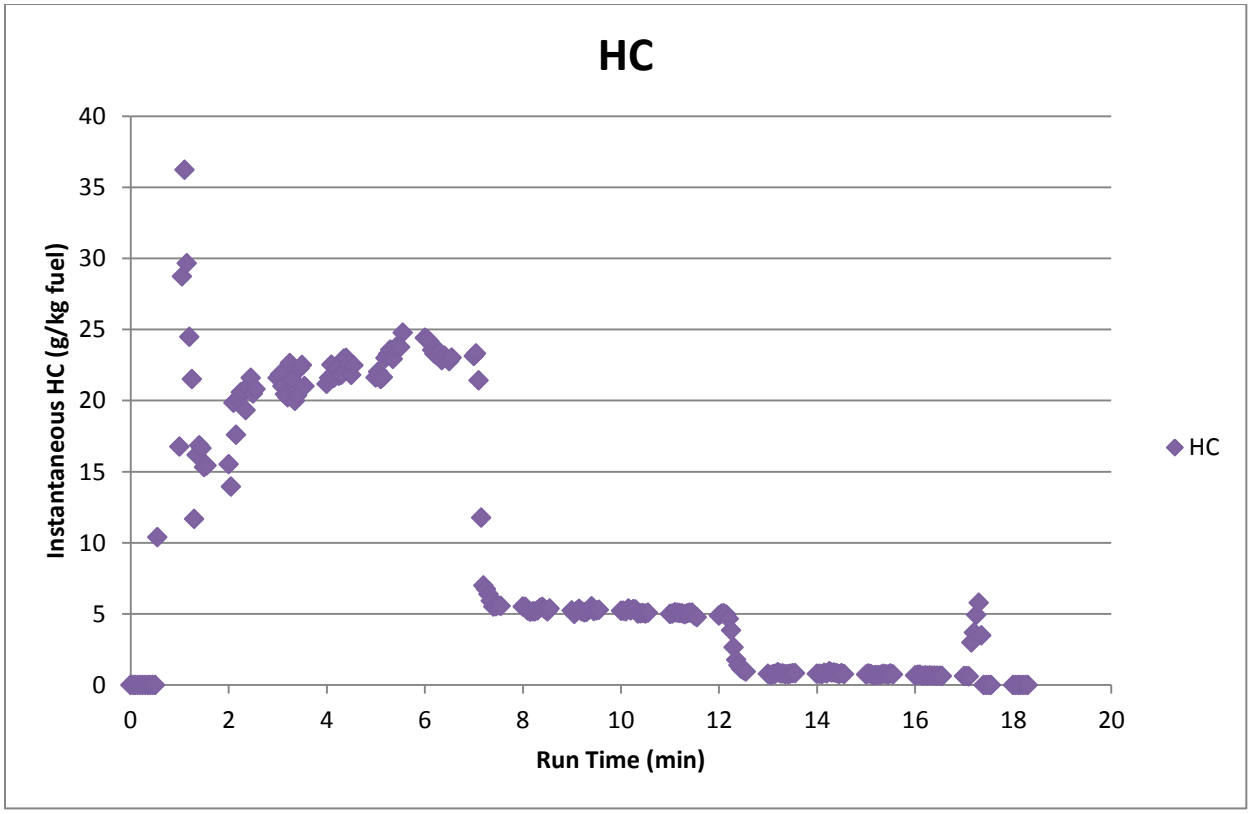


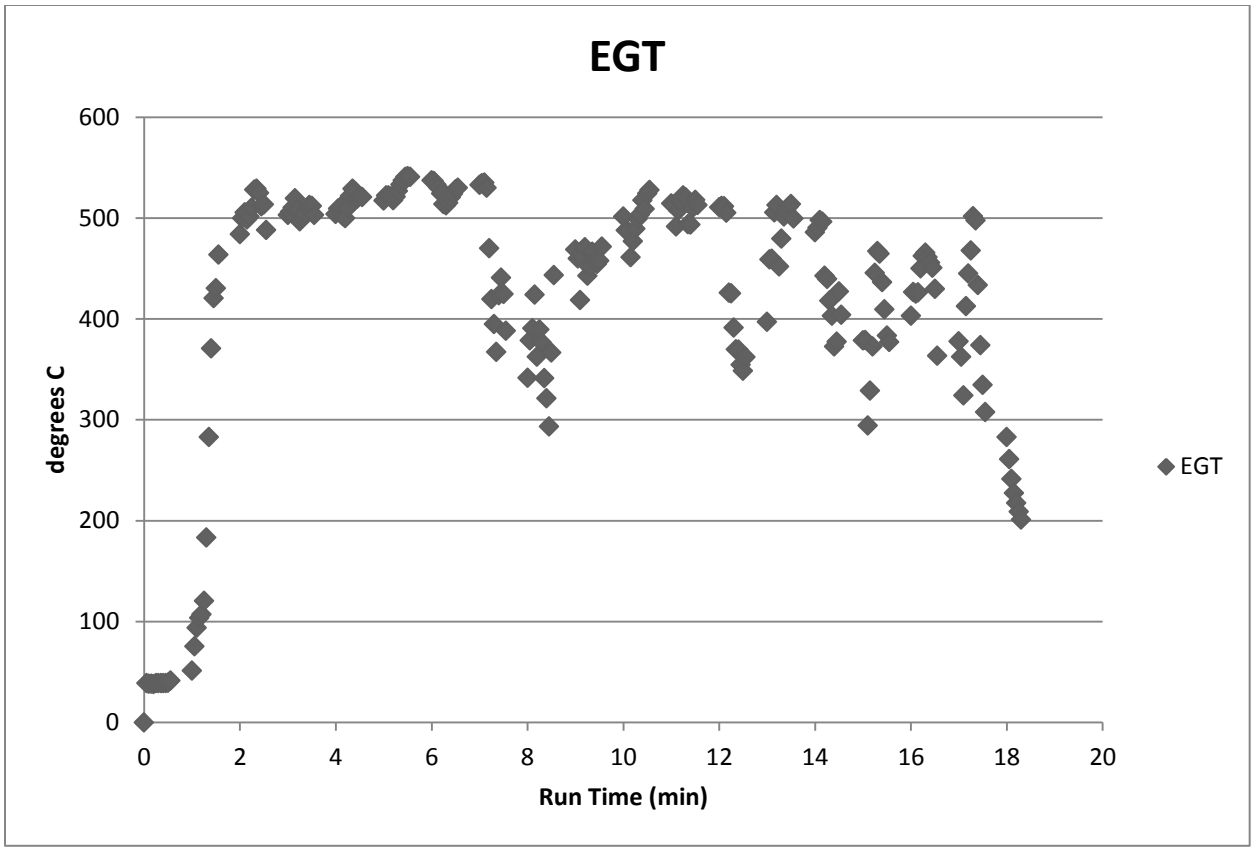


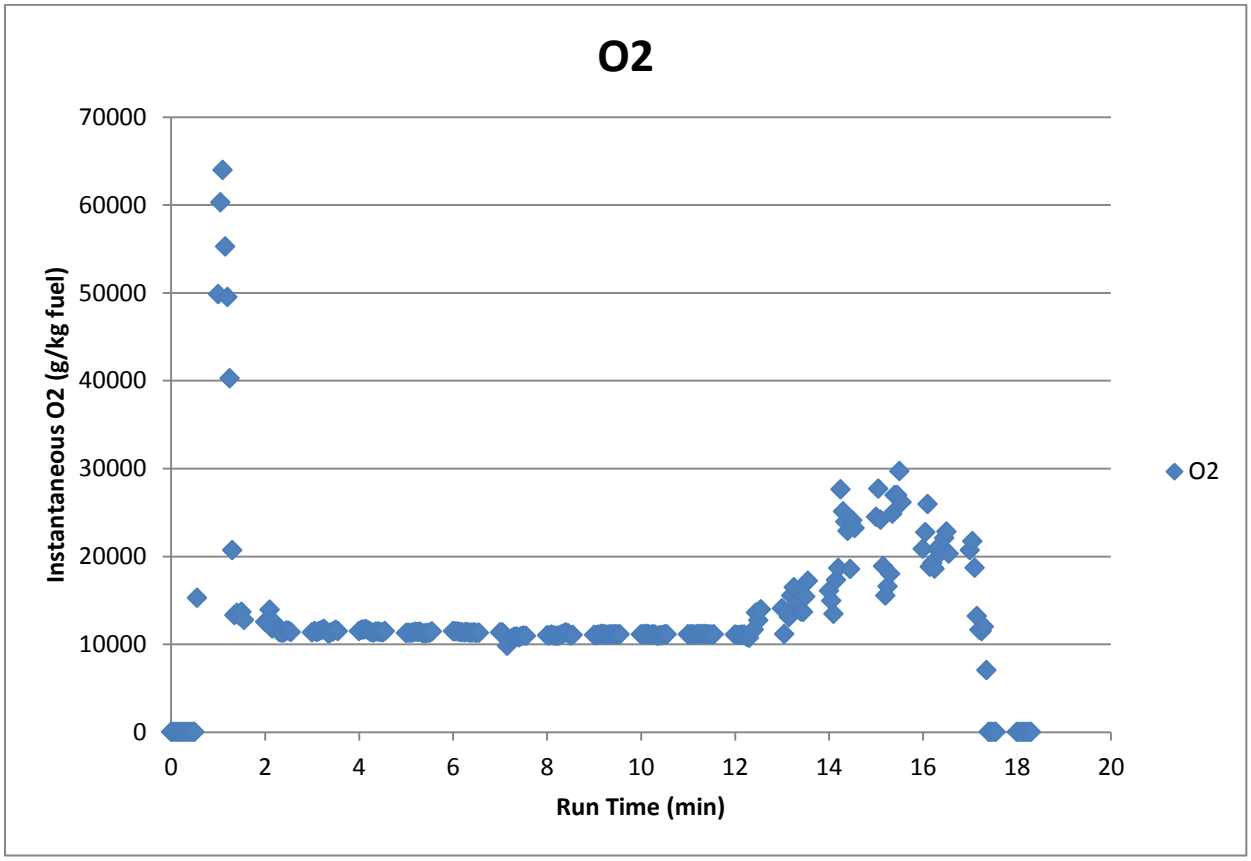

NO
Instantaneous NO (g/kg fuel)
Run Time (min)
NO
0
0.5
1
1.5
2
2.5
3
3.5
4
0
2
4
6
8
10
12
14
16
18
20

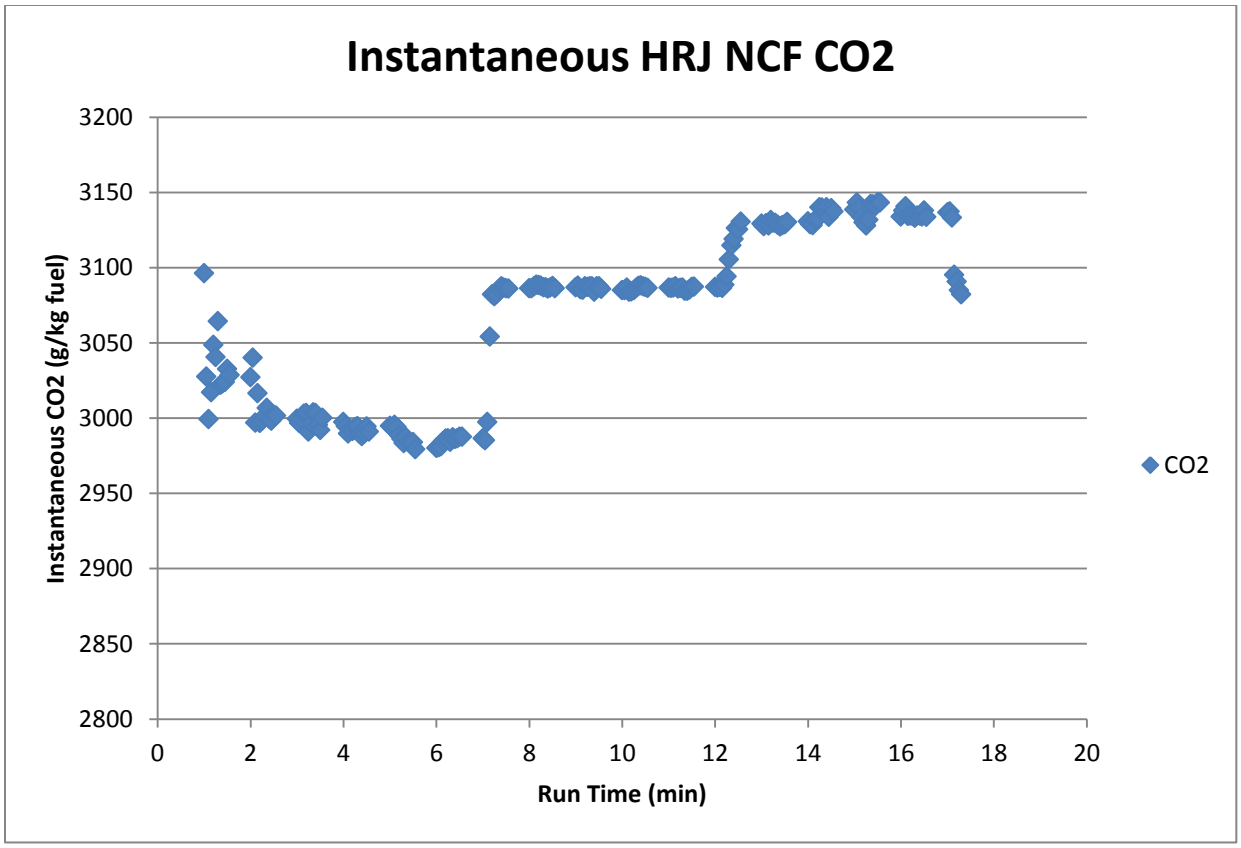

NO2
Instantaneous NO2 (g/kg fuel)
Run Time (min)
NO2
0
0.5
1
1.5
2
2.5
3
0
2
4
6
8
10
12
14
16
18
20

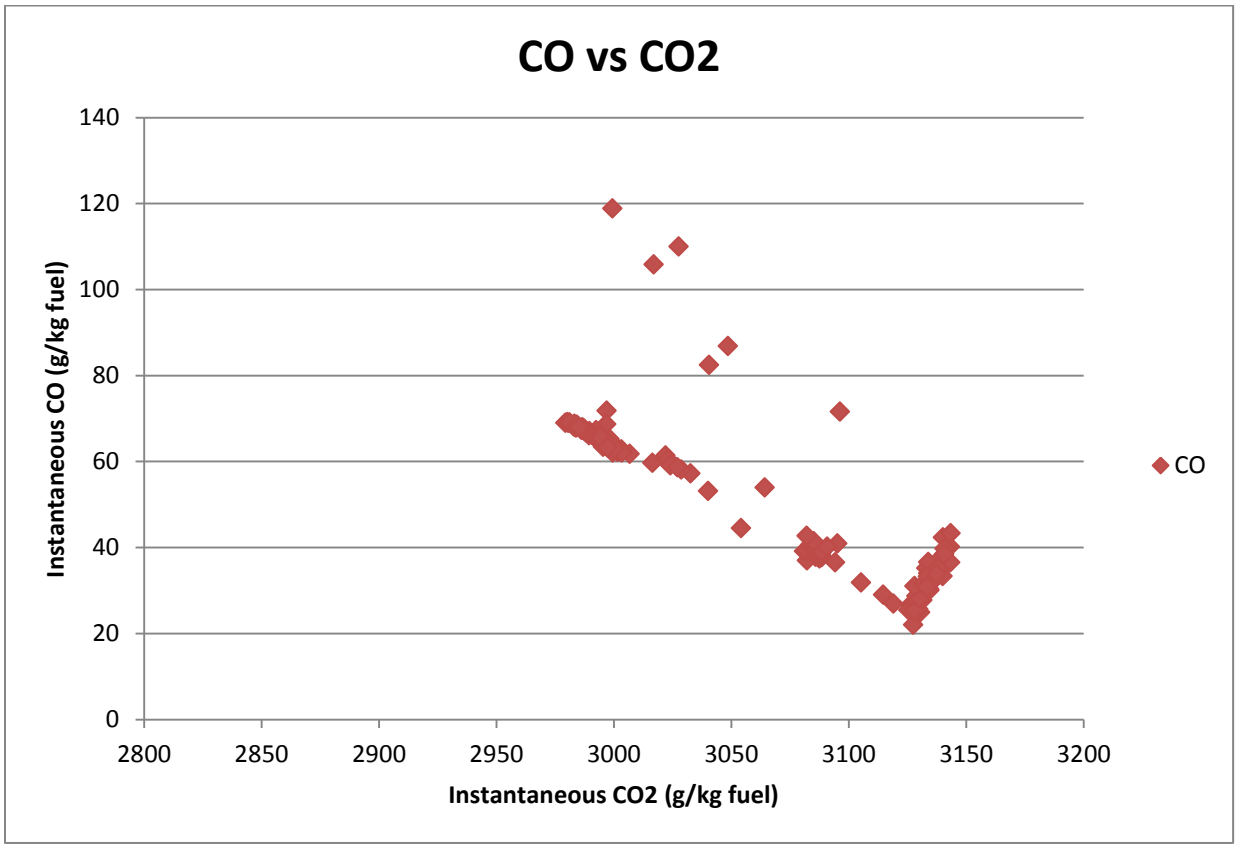

NOx
Instantaneous NOx (g/kg fuel)
3
2.5
2
1.5
1
0.5
0
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
NOx

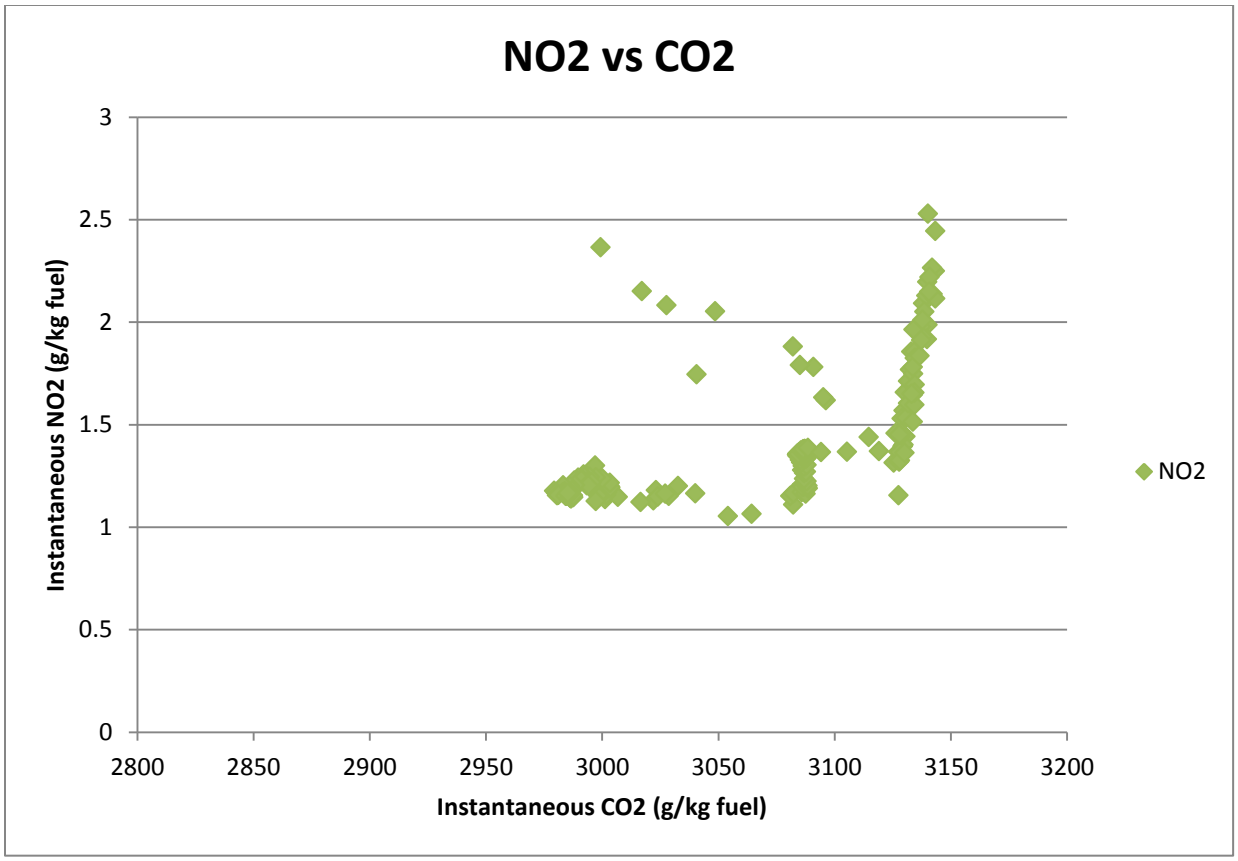

HC
Instantaneous HC (g/kg fuel)
40
35
30
25
20
15
10
5
0
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
HC

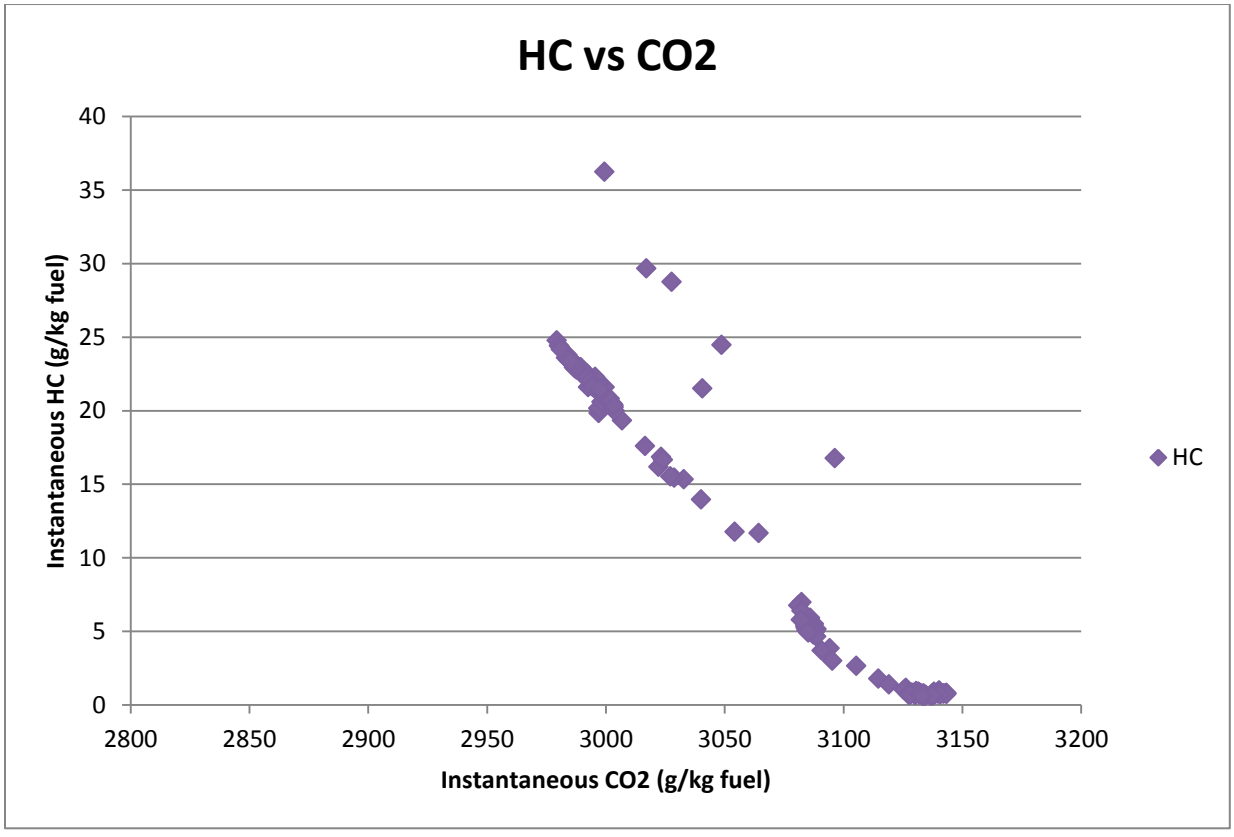

EGT
600
500
400
300
200
100
0
degrees C
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
EGT


O2
70000
60000
50000
40000
30000
20000
10000
0
Instantaneous O2 (g/kg fuel)
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
O2

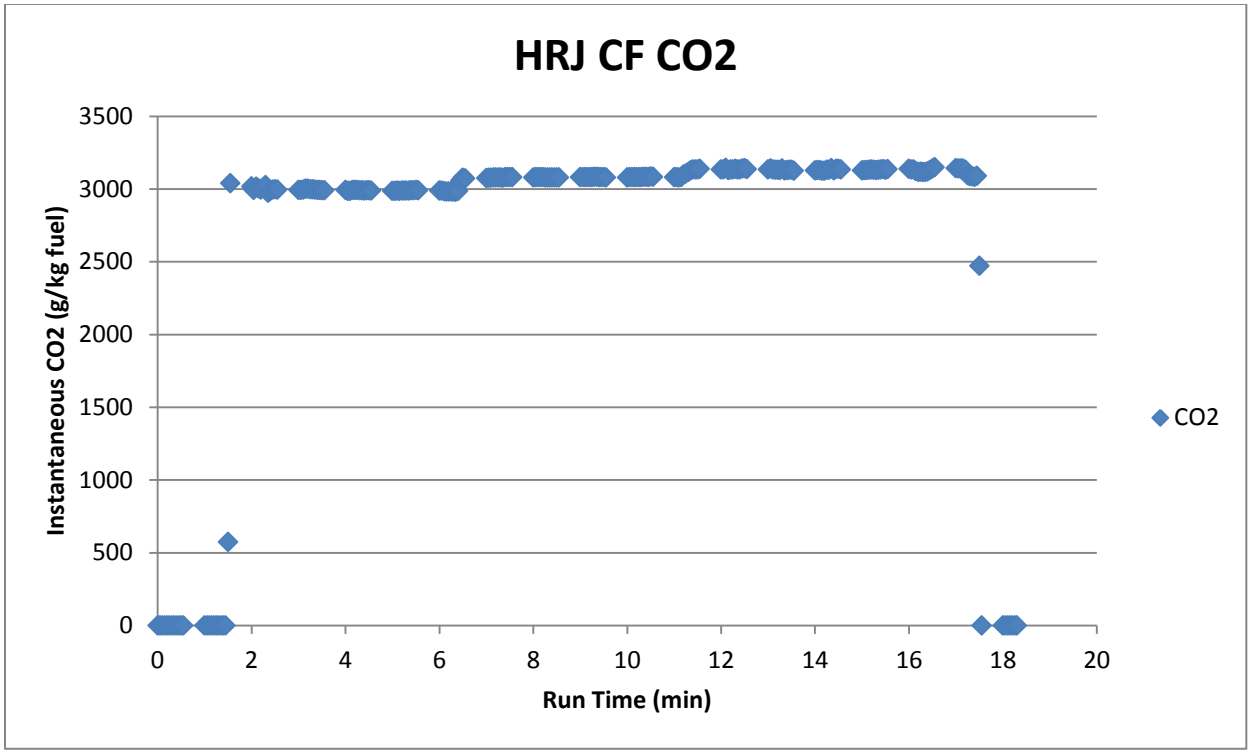

Instantaneous HRJ NCF CO2
Instantaneous CO2 (g/kg fuel)
3200
3150
3100
3050
3000
2950
2900
2850
2800
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
CO2

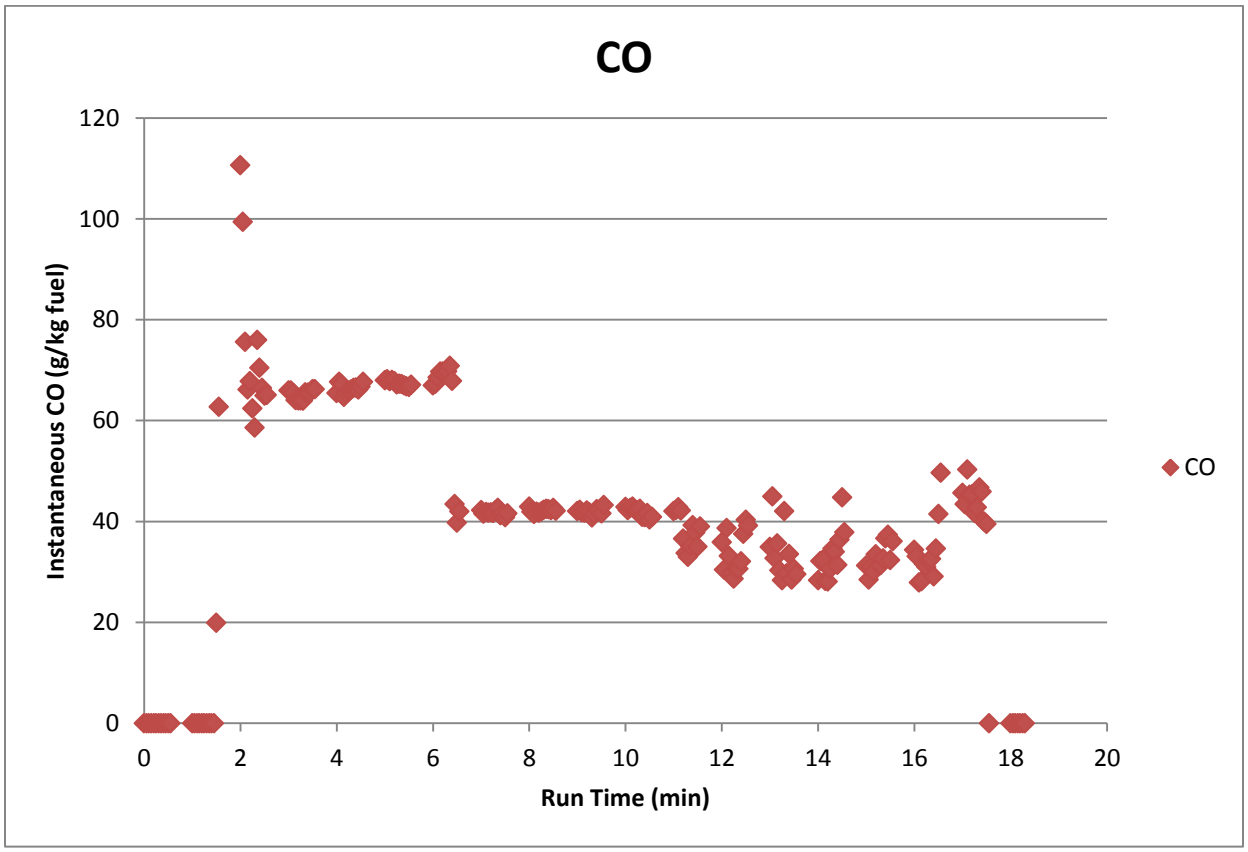

CO vs CO2
Instantaneous CO (g/kg fuel)
140
120
100
80
60
40
20
0
2800
2850
2900
2950
3000
3050
3100
3150
3200
Instantaneous CO2 (g/kg fuel)
CO

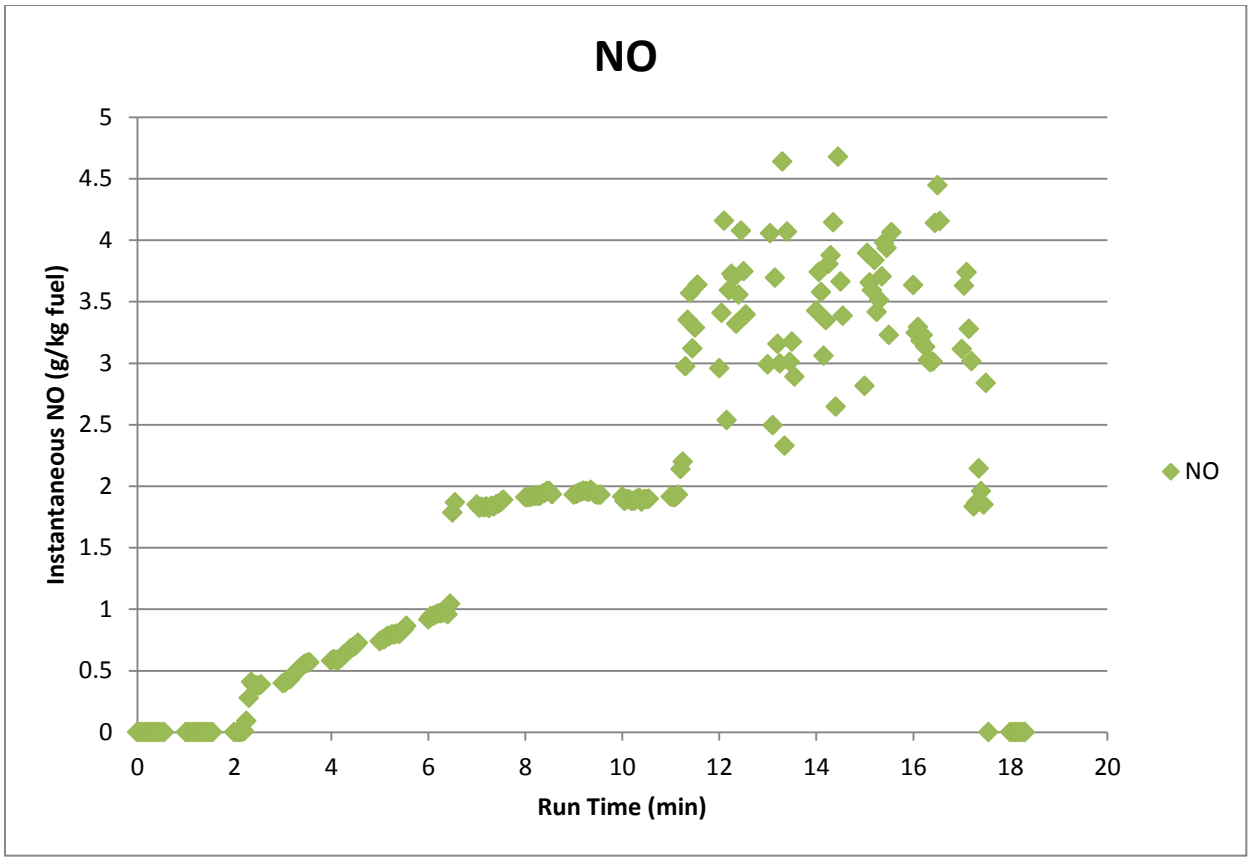

NO2 vs CO2
Instantaneous NO2 (g/kg fuel)
3
2.5
2
1.5
1
0.5
0
2800
2850
2900
2950
3000
3050
3100
3150
3200
Instantaneous CO2 (g/kg fuel)
NO2

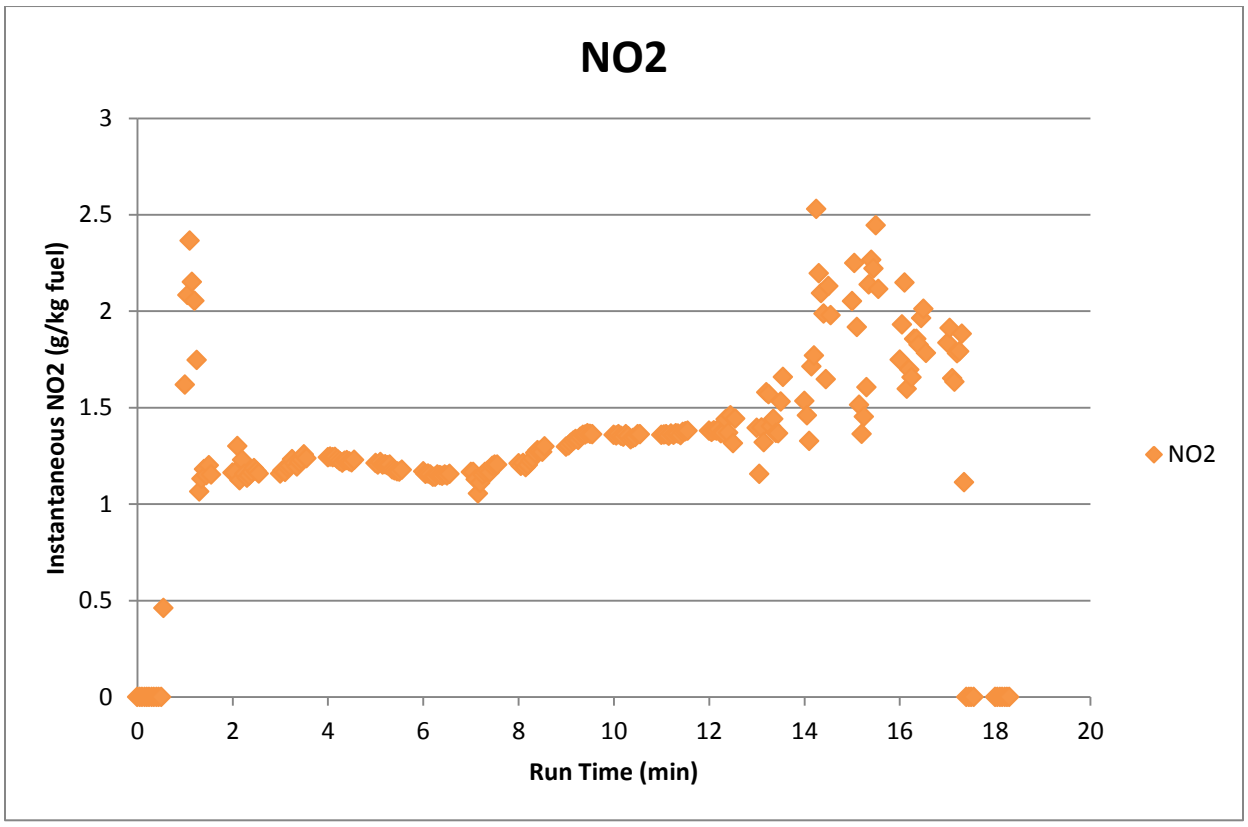

HC vs CO2
Instantaneous HC (g/kg fuel)
40
35
30
25
20
15
10
5
0
2800
2850
2900
2950
3000
3050
3100
3150
3200
Instantaneous CO2 (g/kg fuel)
HC

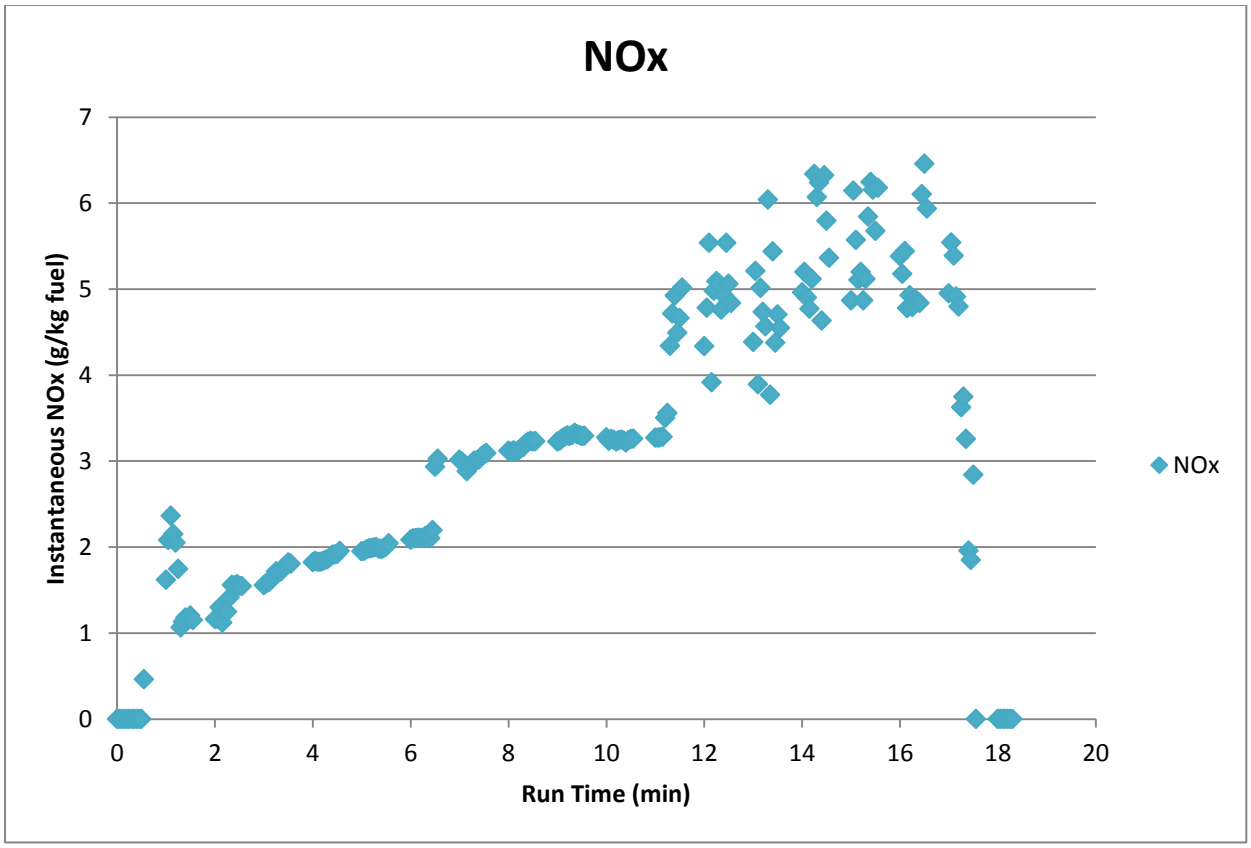
Salina3 HRJ CF 9/12/2012 PT6

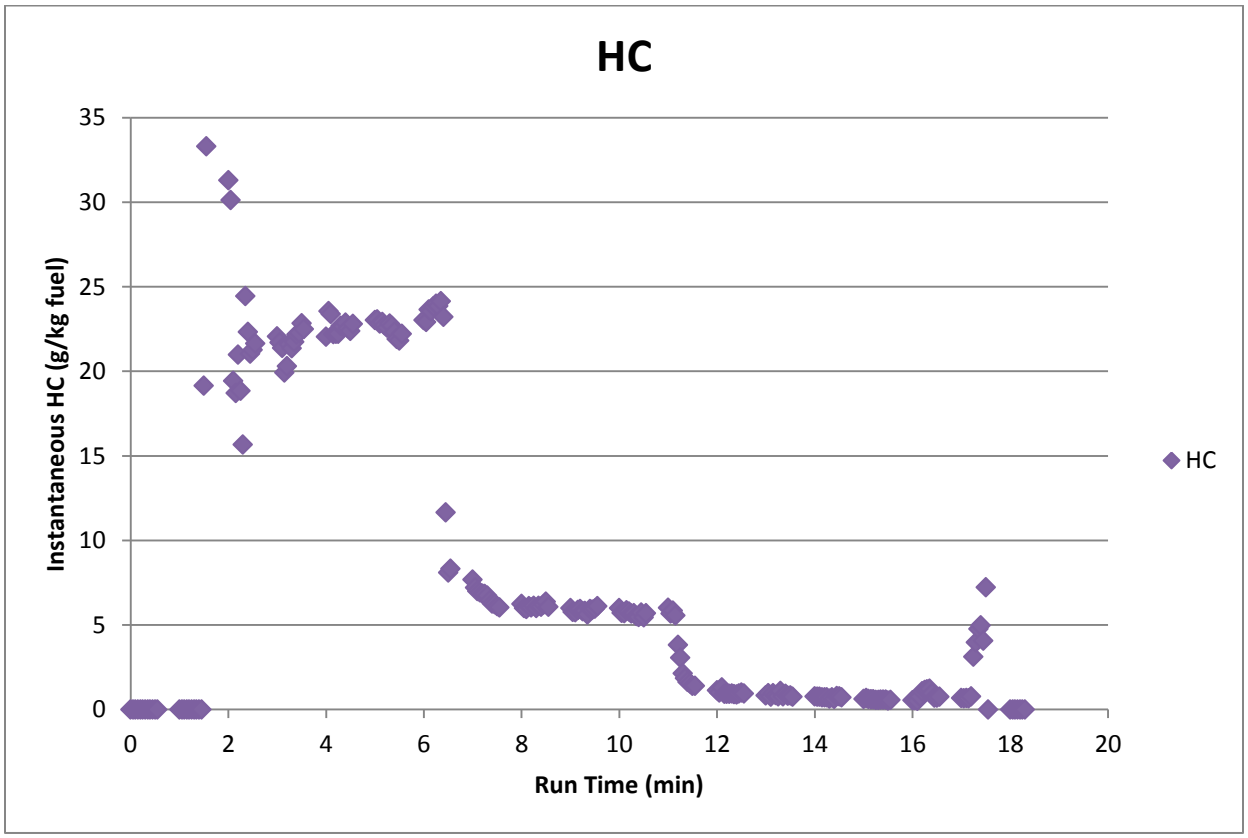


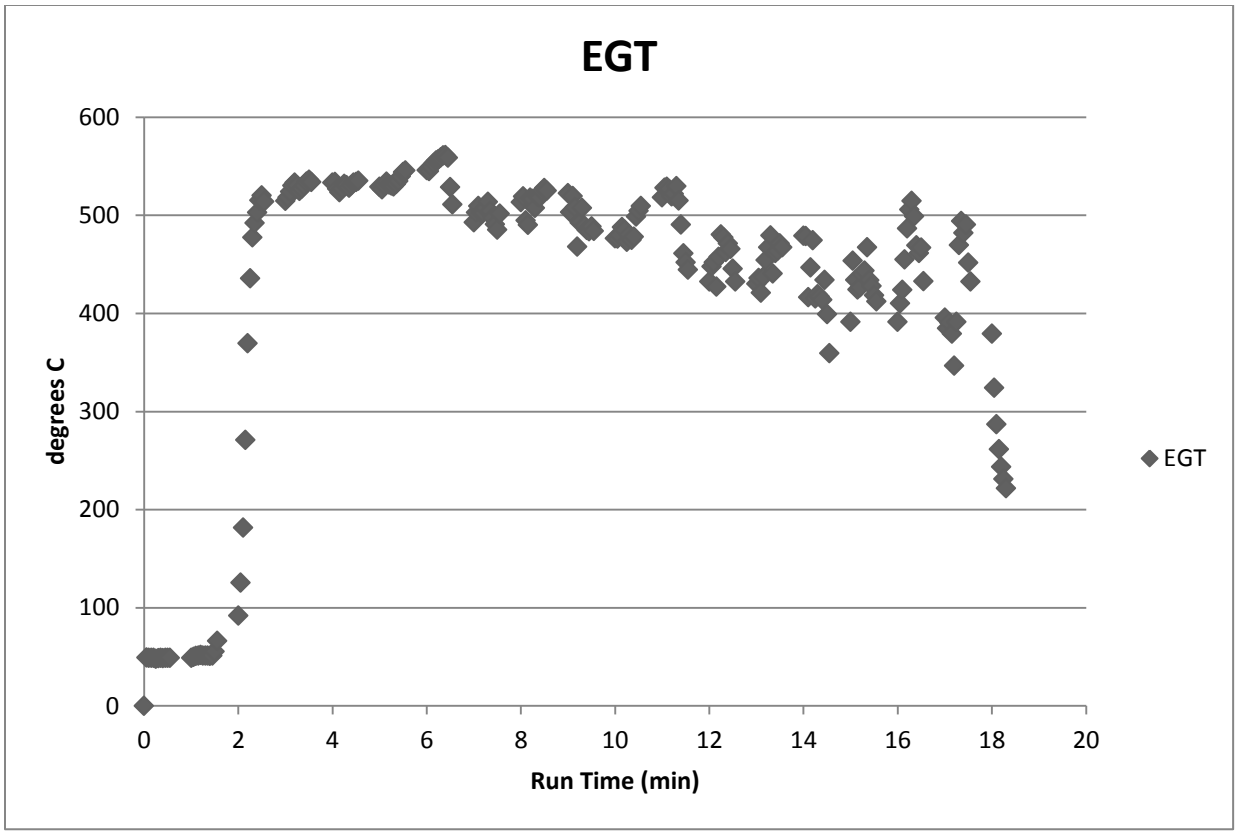


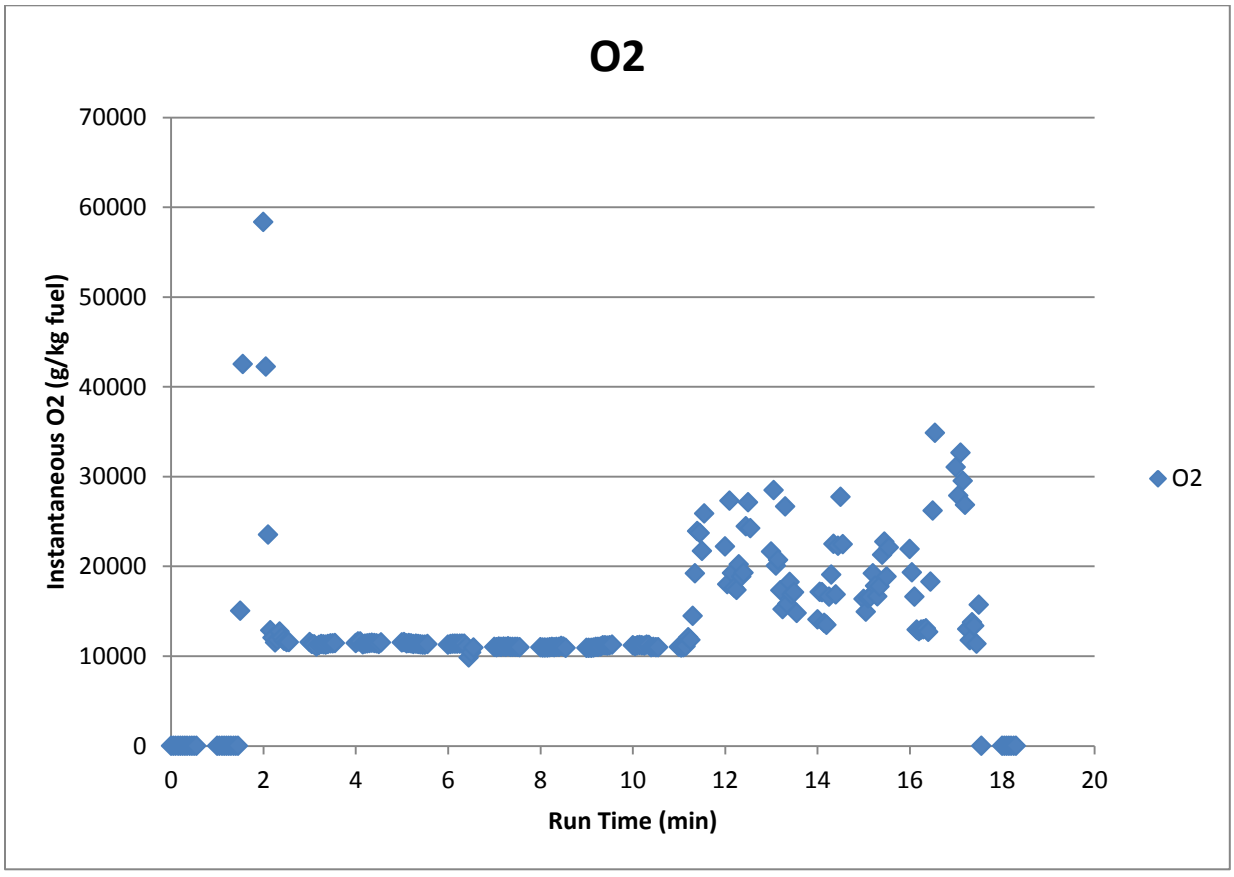

NO
Instantaneous NO (g/kg fuel)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
NO

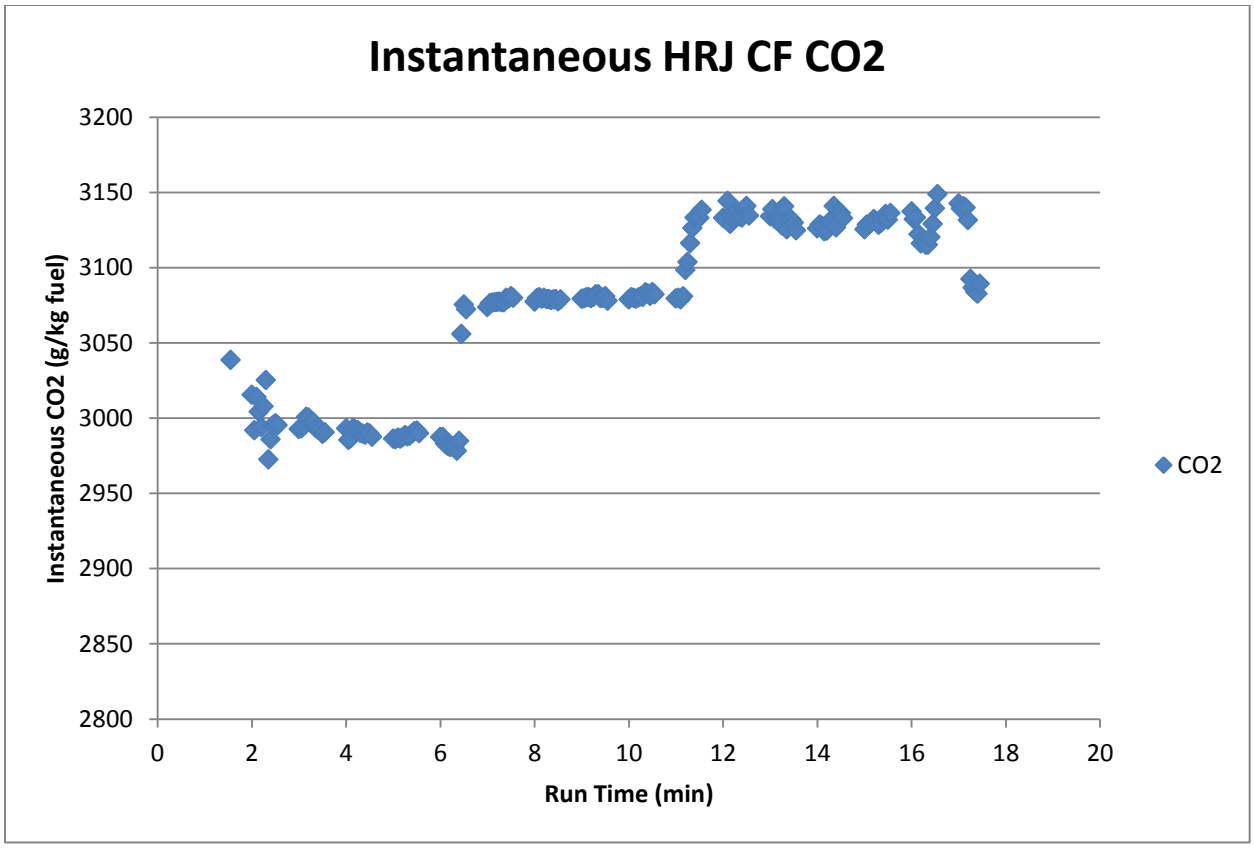

NO2
Instantaneous NO2 (g/kg fuel)
0
0.5
1
1.5
2
2.5
3
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
NO2

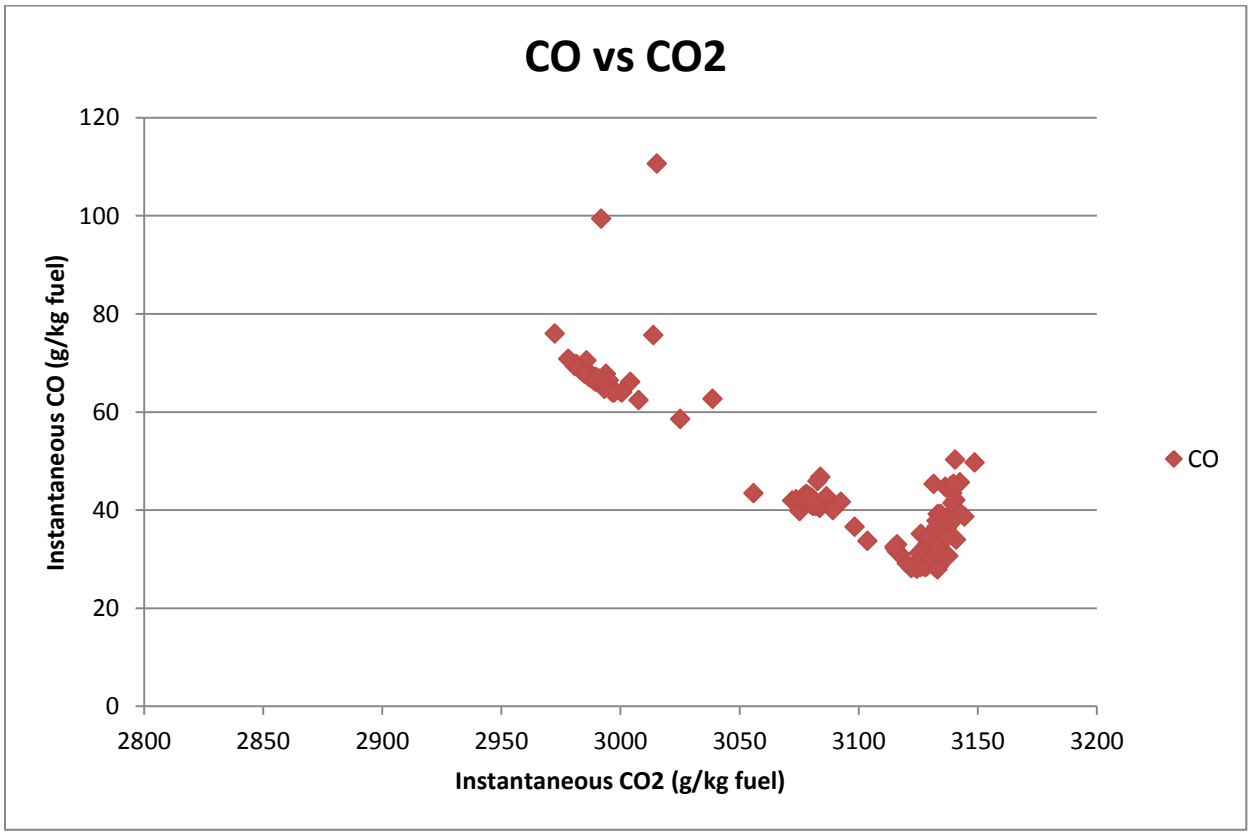

NOx
Instantaneous NOx (g/kg fuel)
0
1
2
3
4
5
6
7
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
NOx

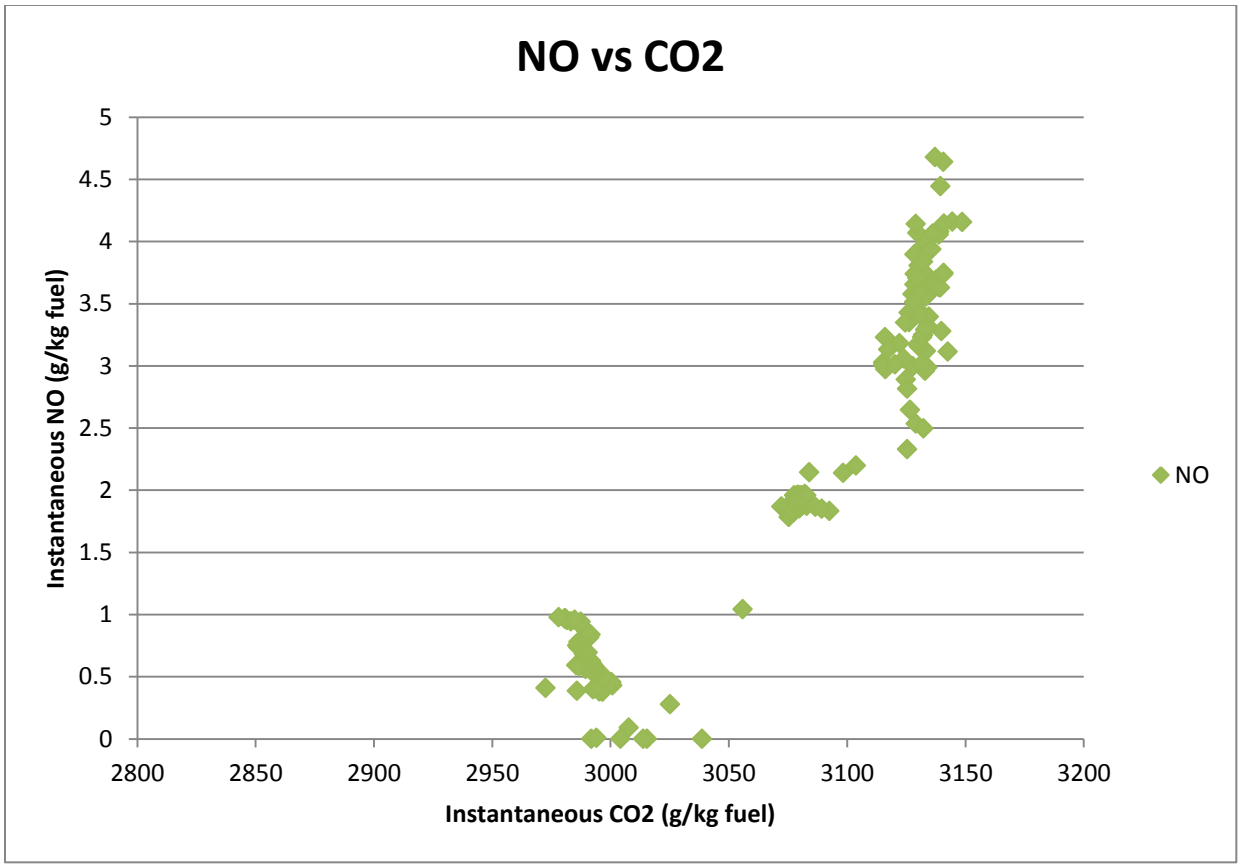

HC
Instantaneous HC (g/kg fuel)
0
5
10
15
20
25
30
35
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
HC

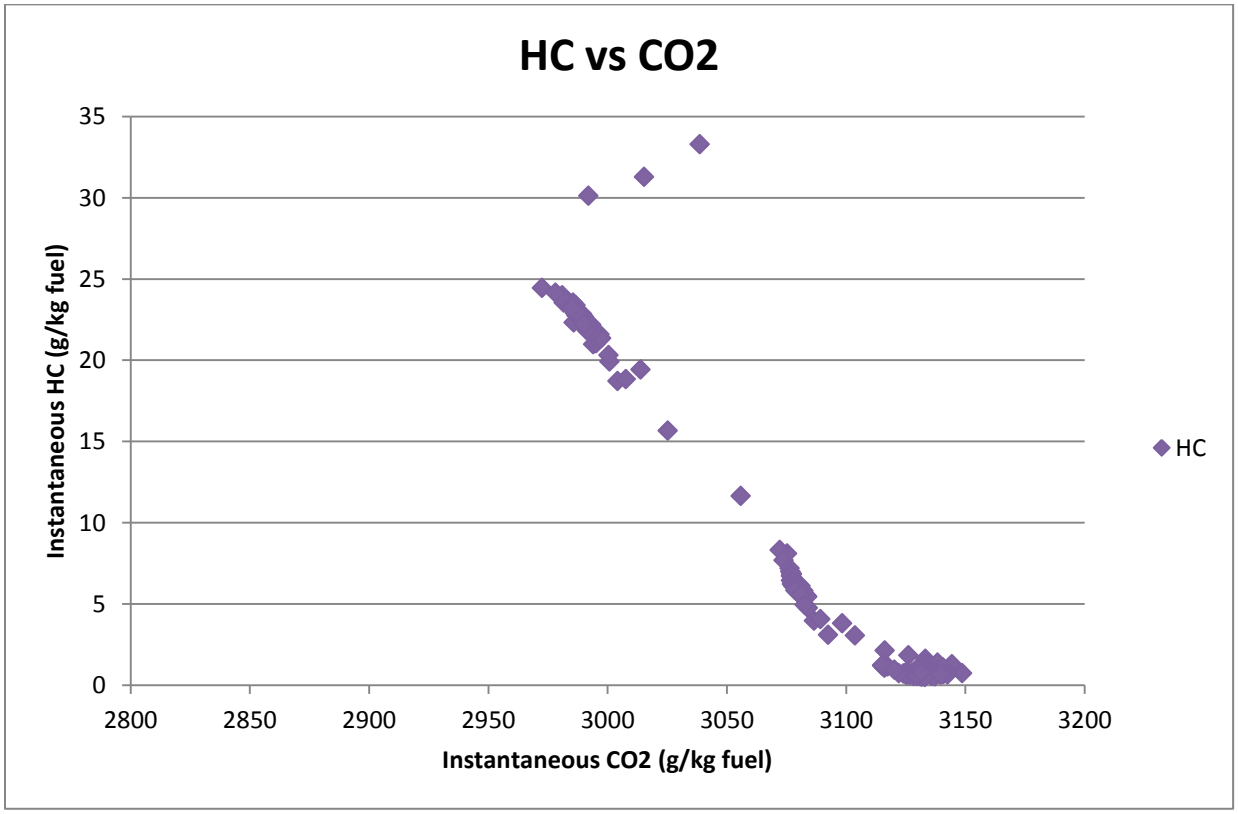

EGT
600
500
400
300
200
100
0
degrees C
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
EGT


O2
70000
60000
50000
40000
30000
20000
10000
0
Instantaneous O2 (g/kg fuel)
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
O2

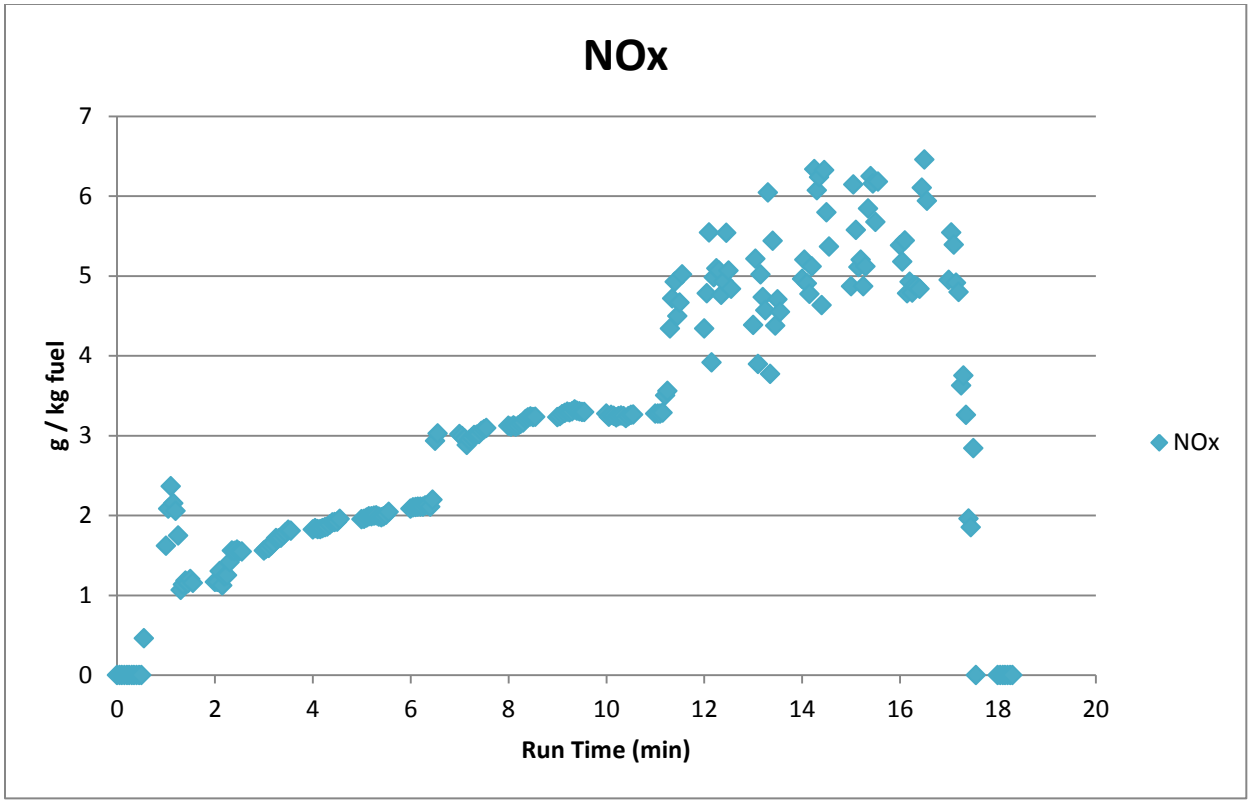

Instantaneous HRJ CF CO2
Instantaneous CO2 (g/kg fuel)
3200
3150
3100
3050
3000
2950
2900
2850
2800
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
CO2

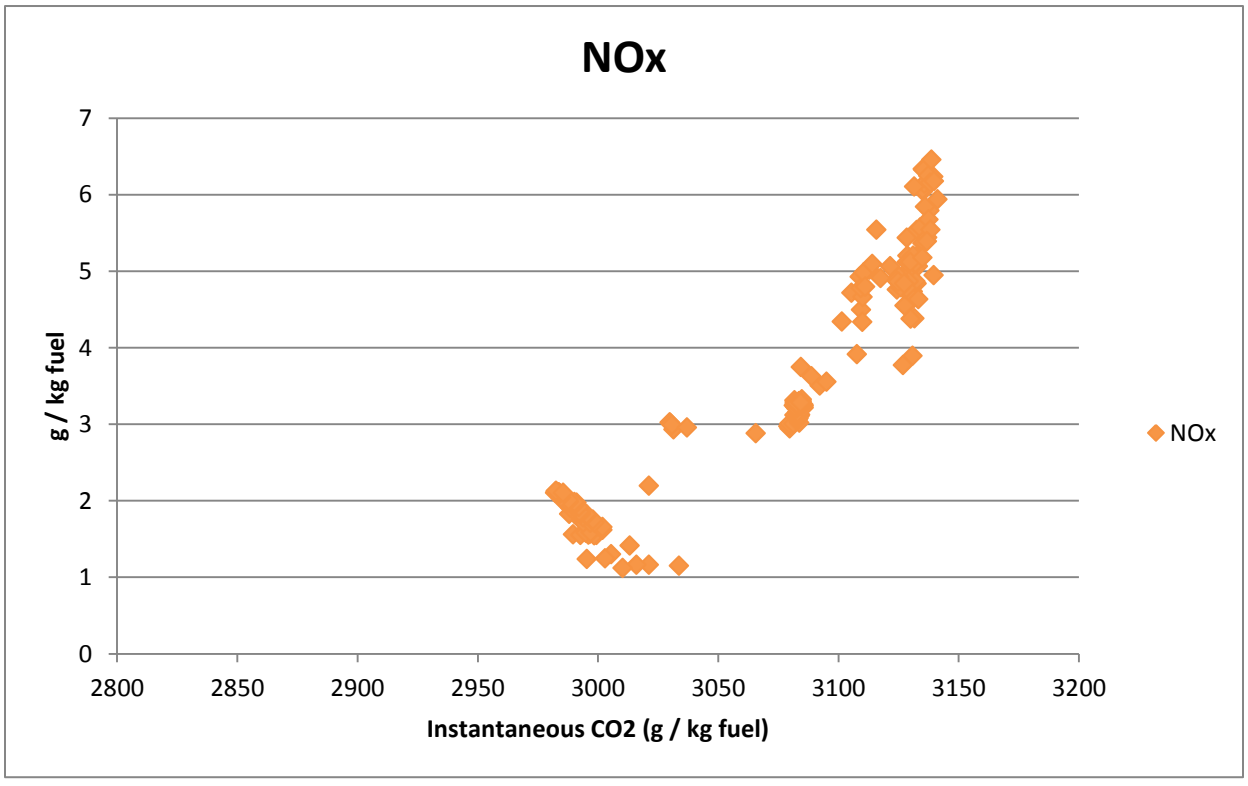

CO vs CO2
Instantaneous CO (g/kg fuel)
120
100
80
60
40
20
0
2800
2850
2900
2950
3000
3050
3100
3150
3200
Instantaneous CO2 (g/kg fuel)
CO


NO vs CO2
Instantaneous NO (g/kg fuel)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
2800
2850
2900
2950
3000
3050
3100
3150
3200
Instantaneous CO2 (g/kg fuel)
NO

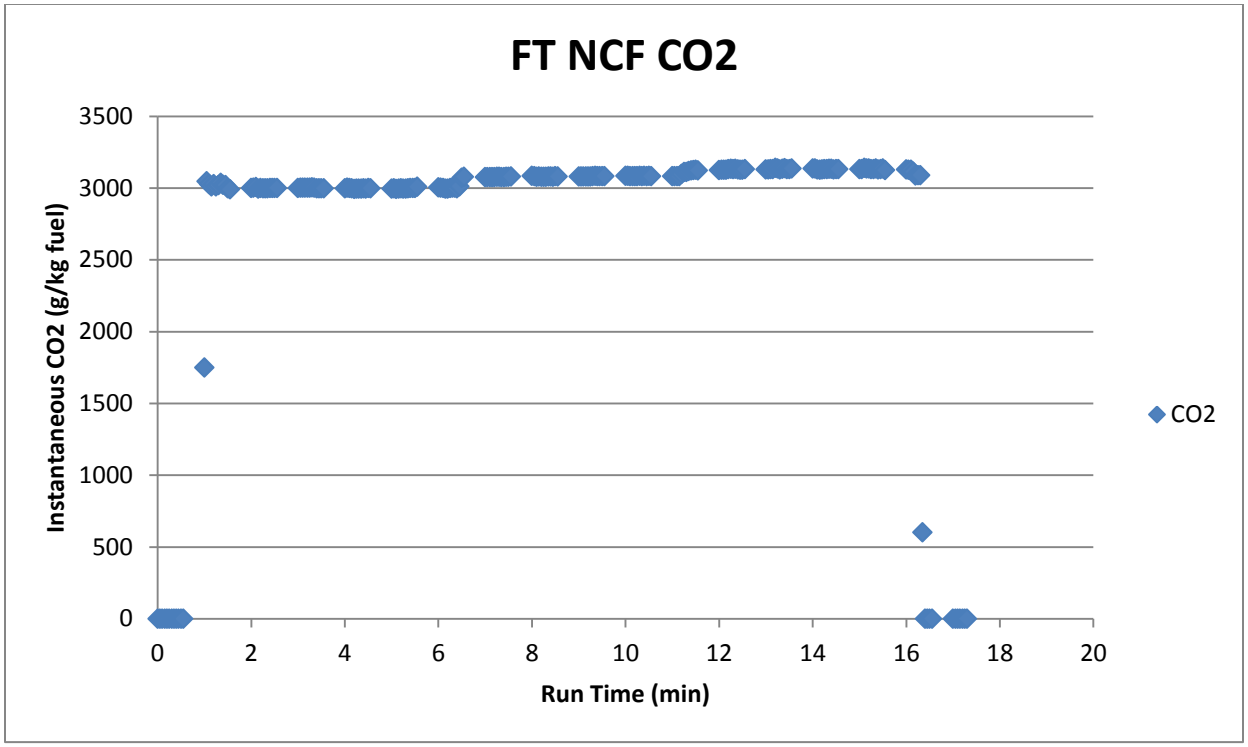

HC vs CO2
Instantaneous HC (g/kg fuel)
35
30
25
20
15
10
5
0
2800
2850
2900
2950
3000
3050
3100
3150
3200
Instantaneous CO2 (g/kg fuel)
HC

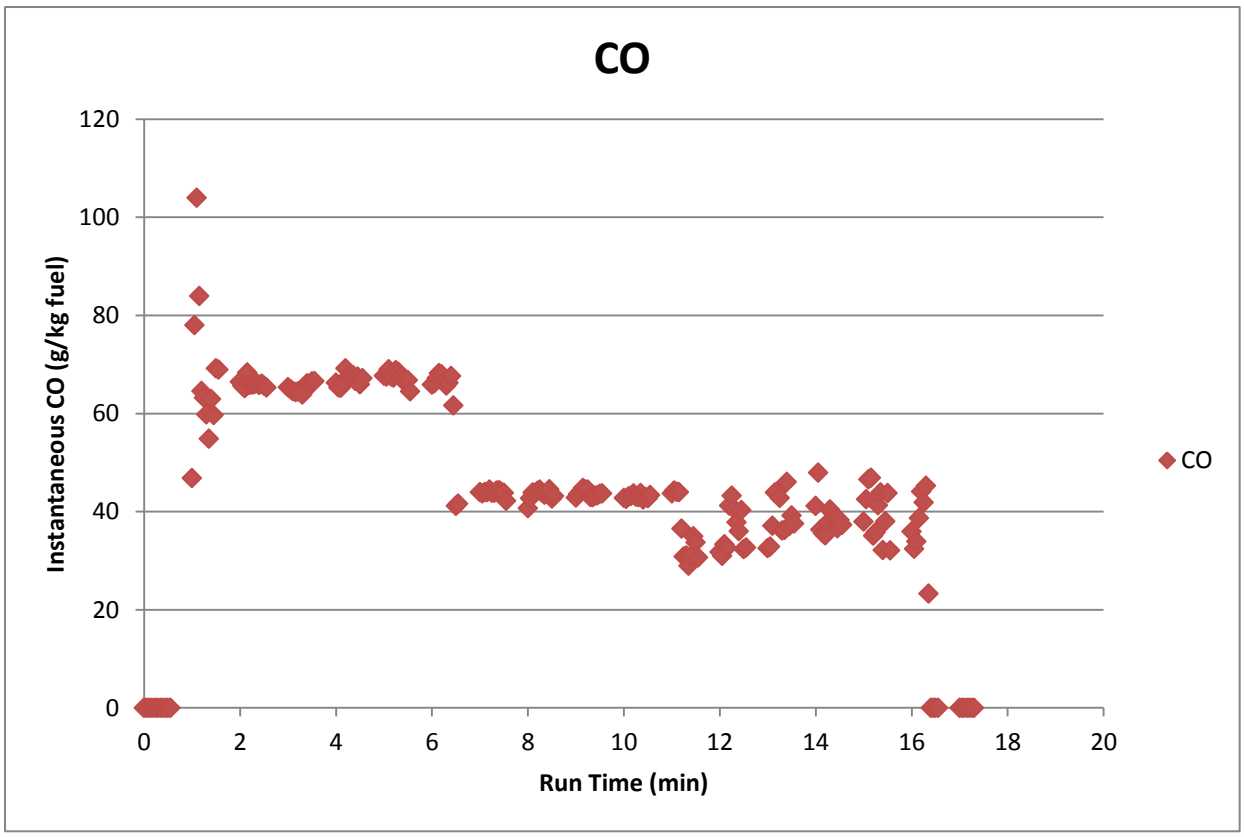
Salina3 HRJ Combined NOx 9/12/2012 PT6

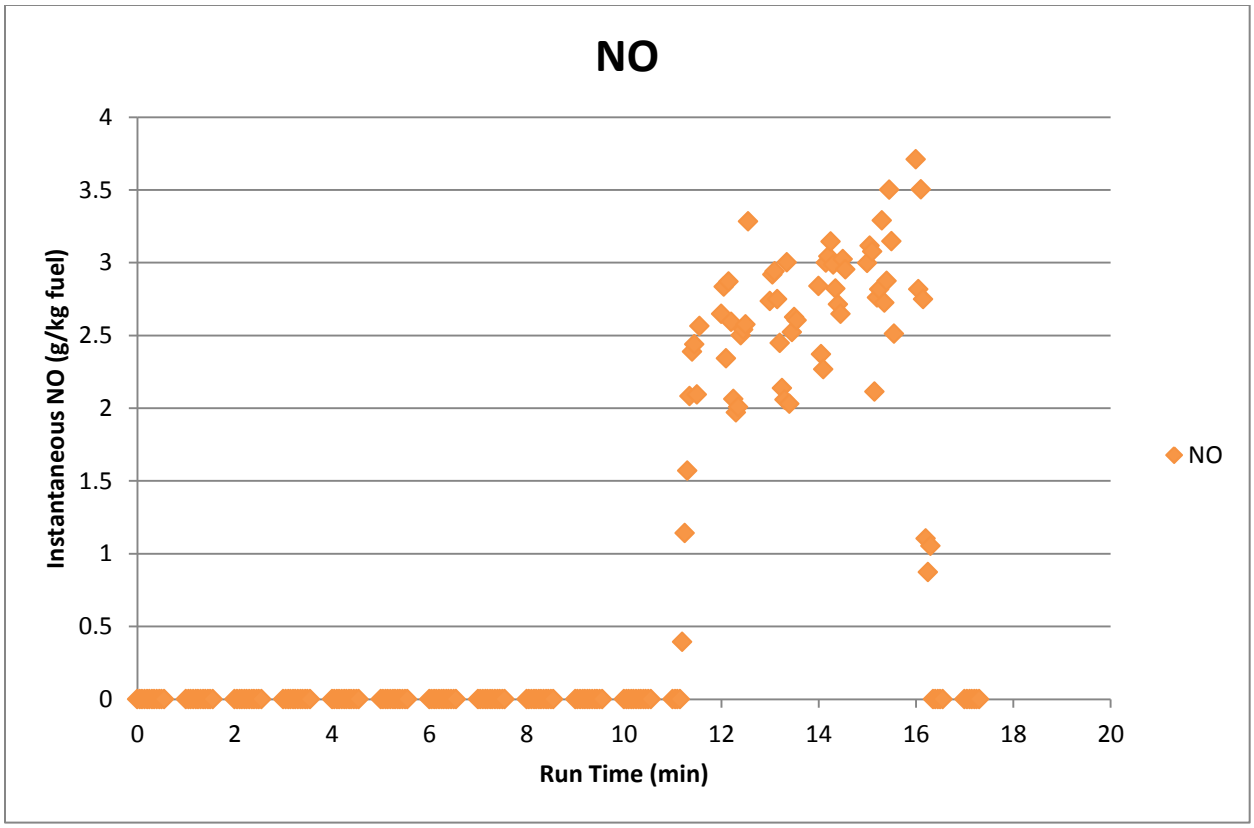


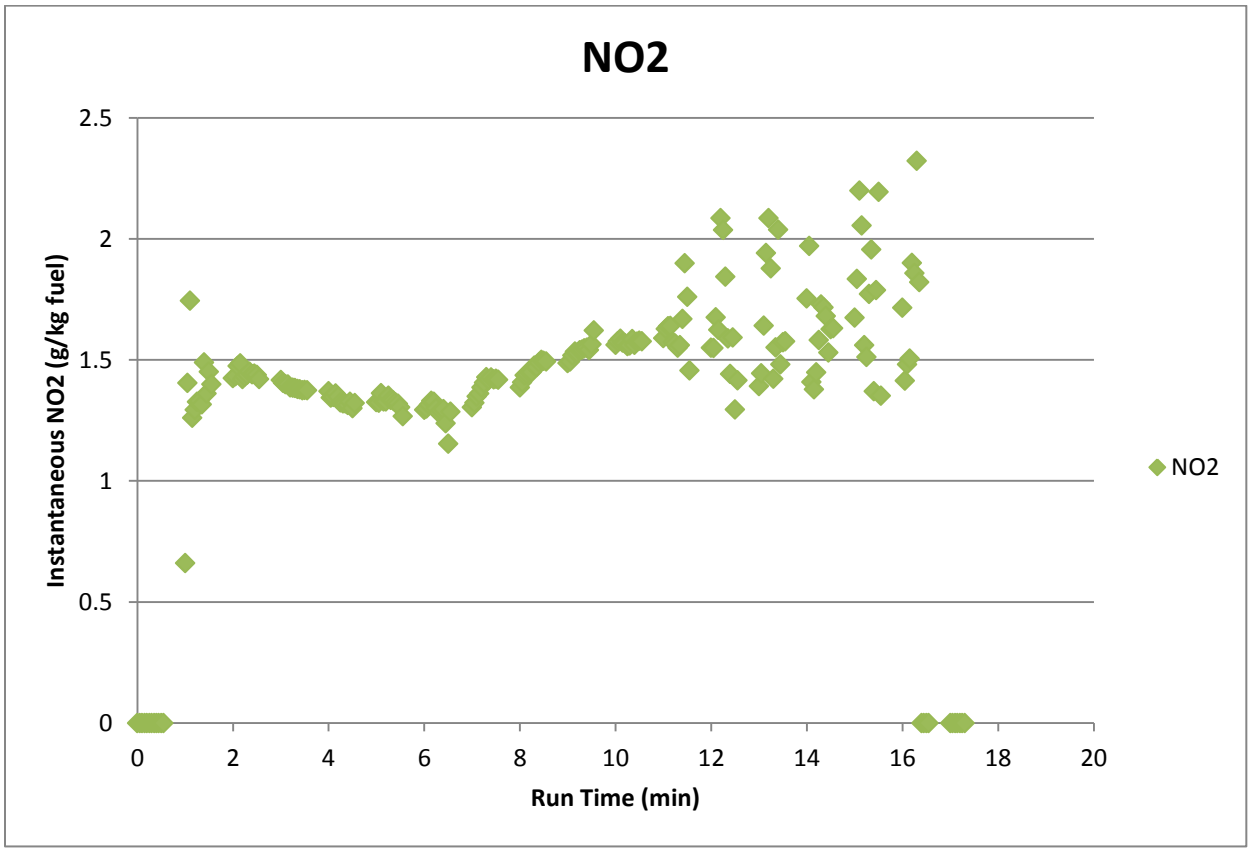


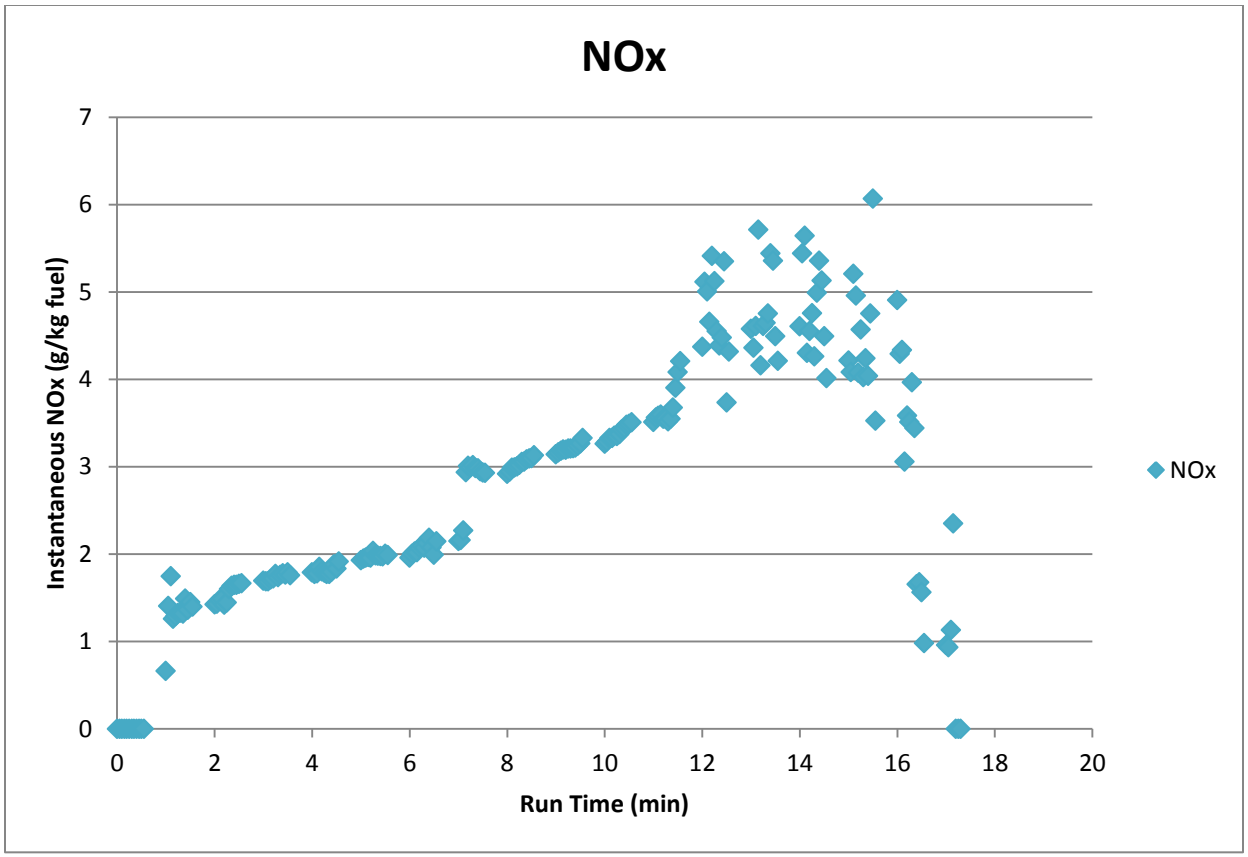
Salina3 FT NCF 9/12/2012 PT6

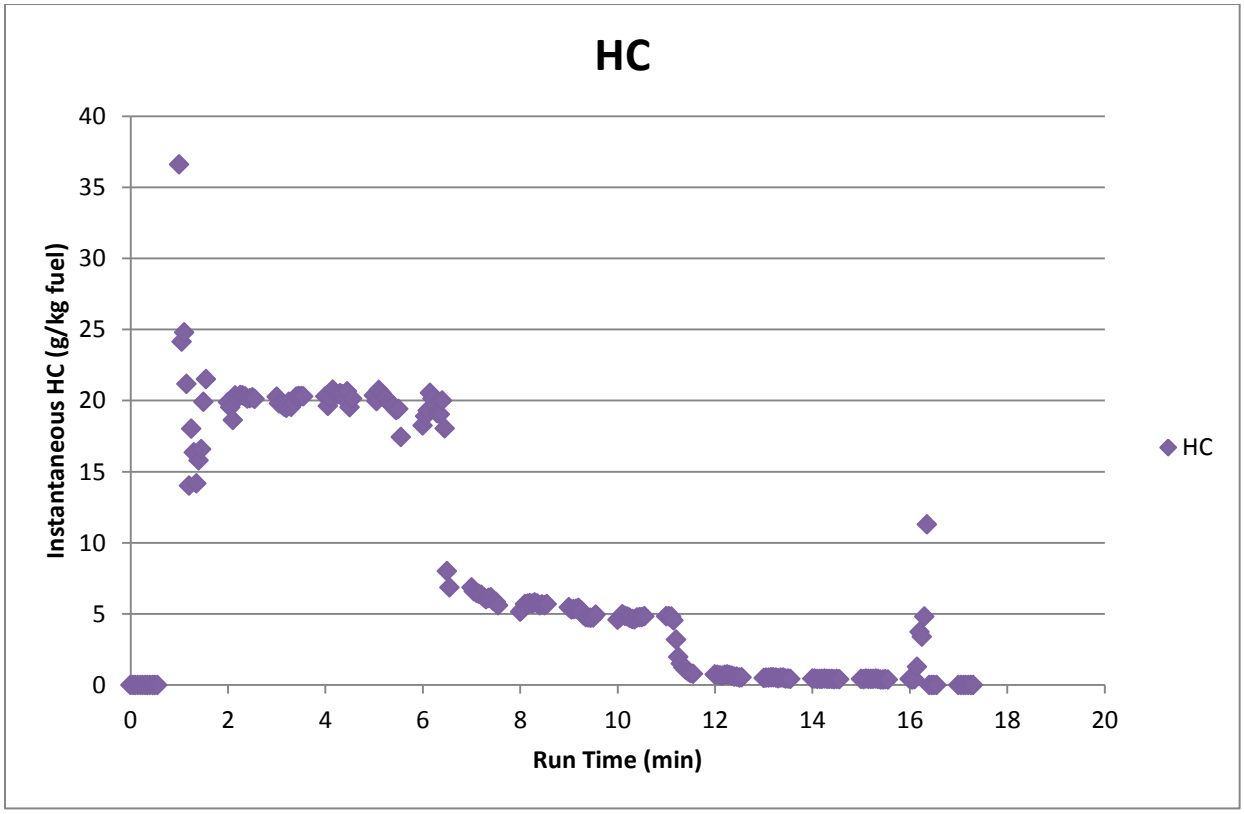


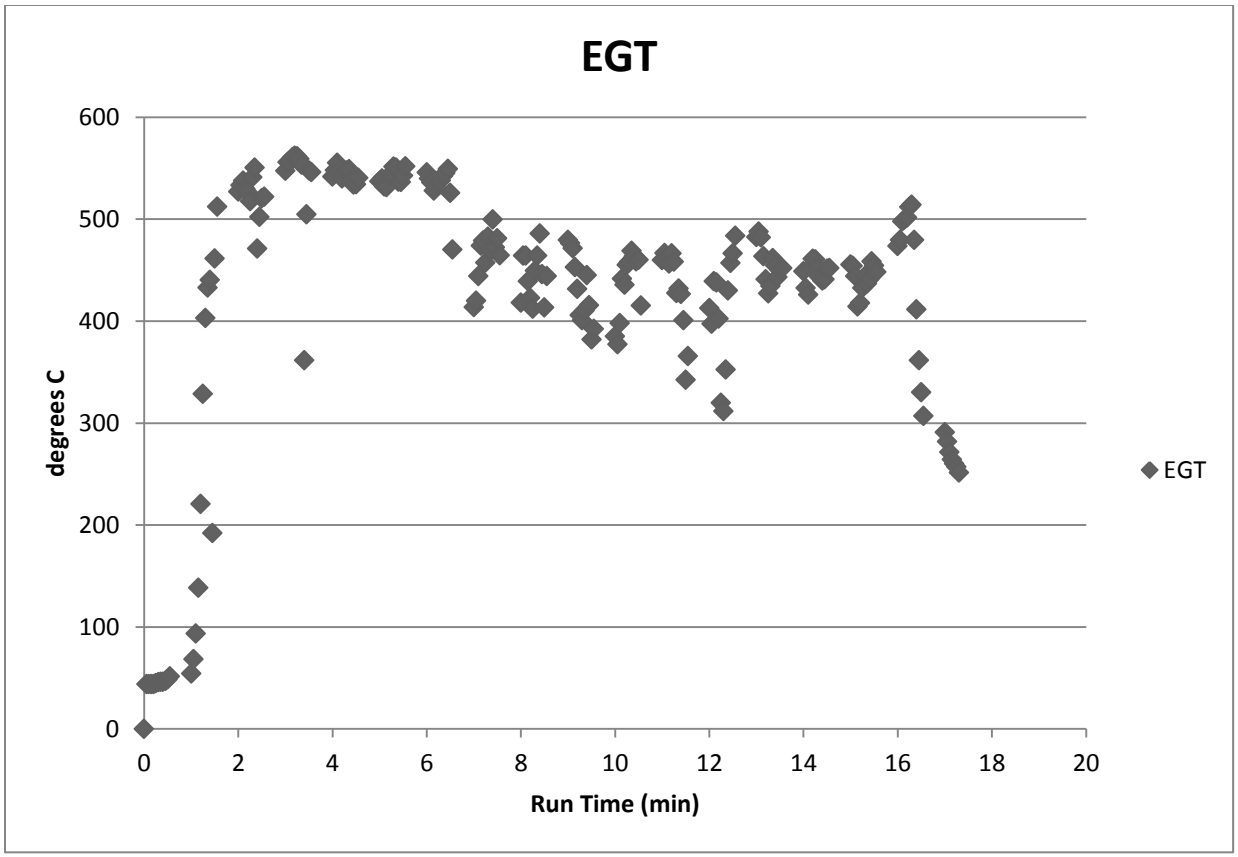


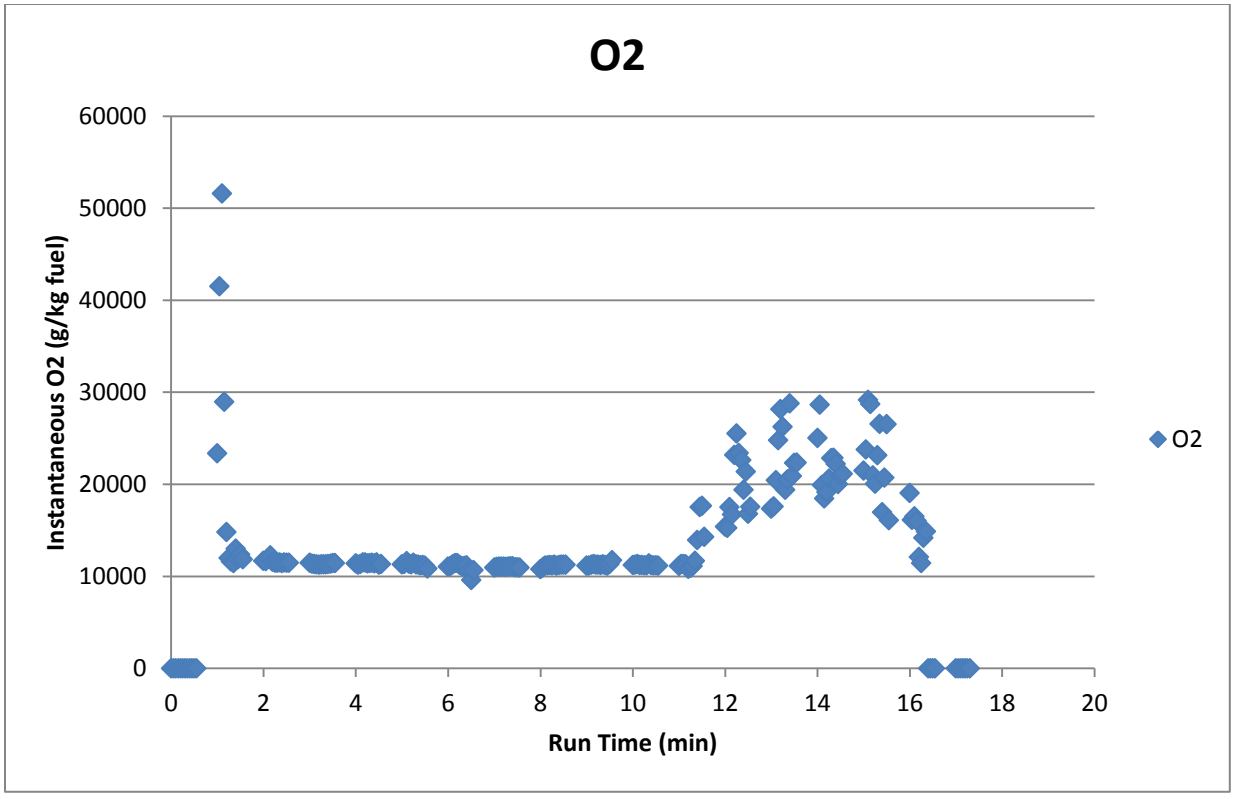

NO
Instantaneous NO (g/kg fuel)
4
3.5
3
2.5
2
1.5
1
0.5
0
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
NO

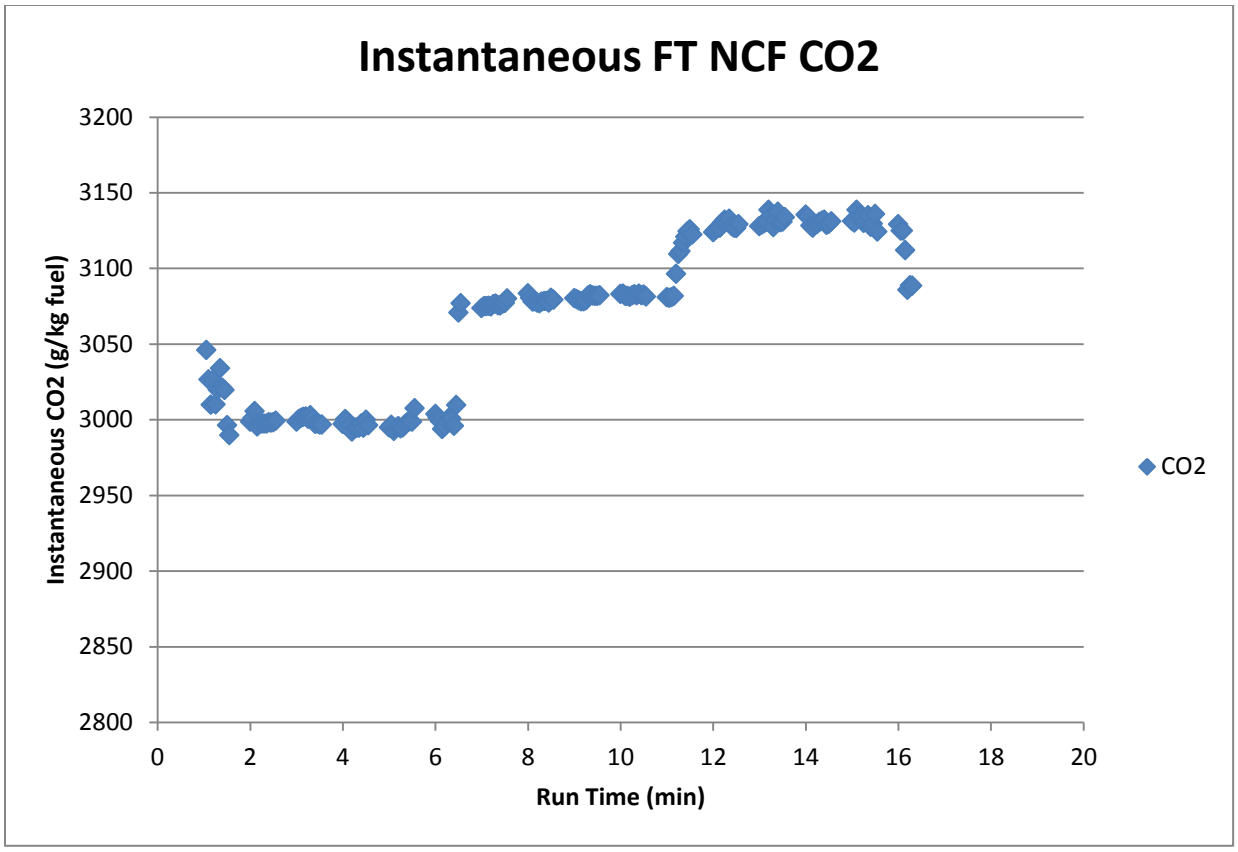

NO2
Instantaneous NO2 (g/kg fuel)
2.5
2
1.5
1
0.5
0
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
NO2

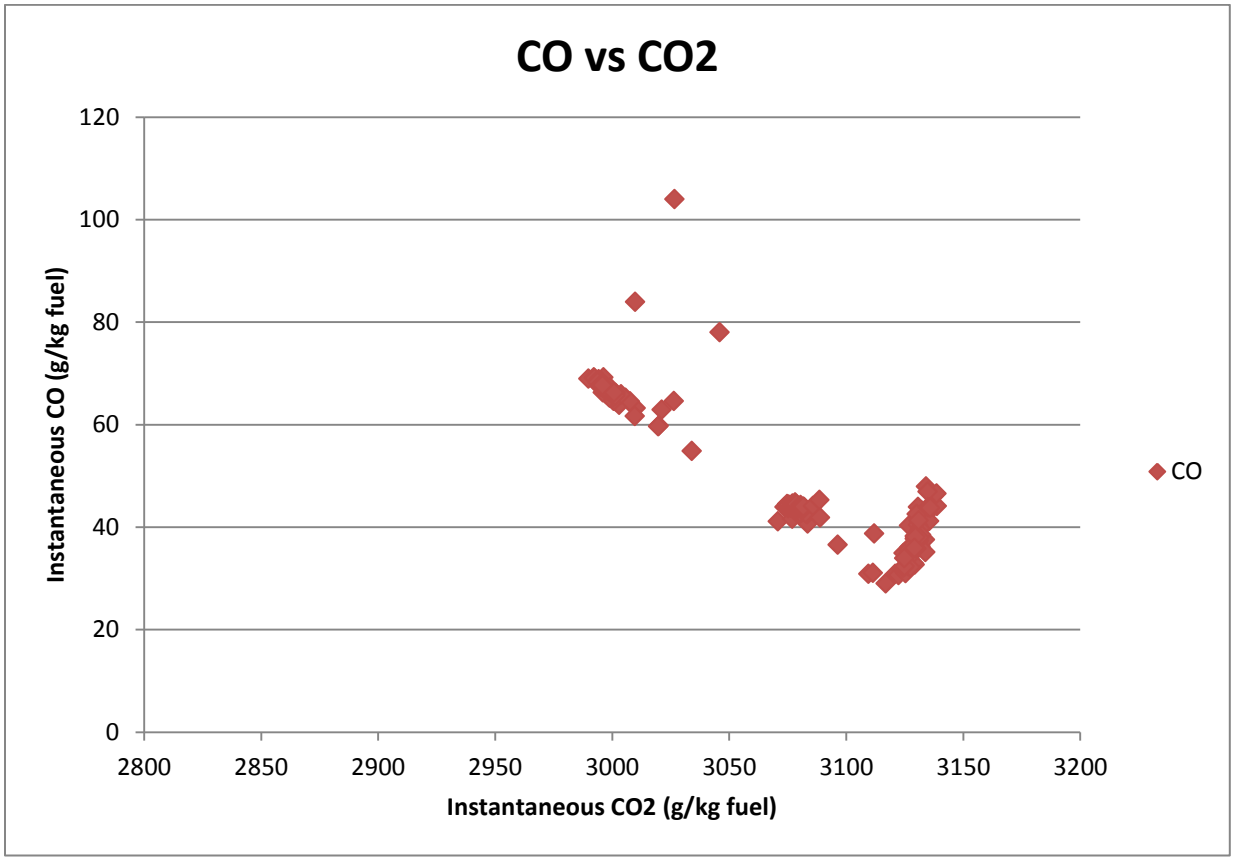

NOx
Instantaneous NOx (g/kg fuel)
0
1
2
3
4
5
6
7
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
NOx

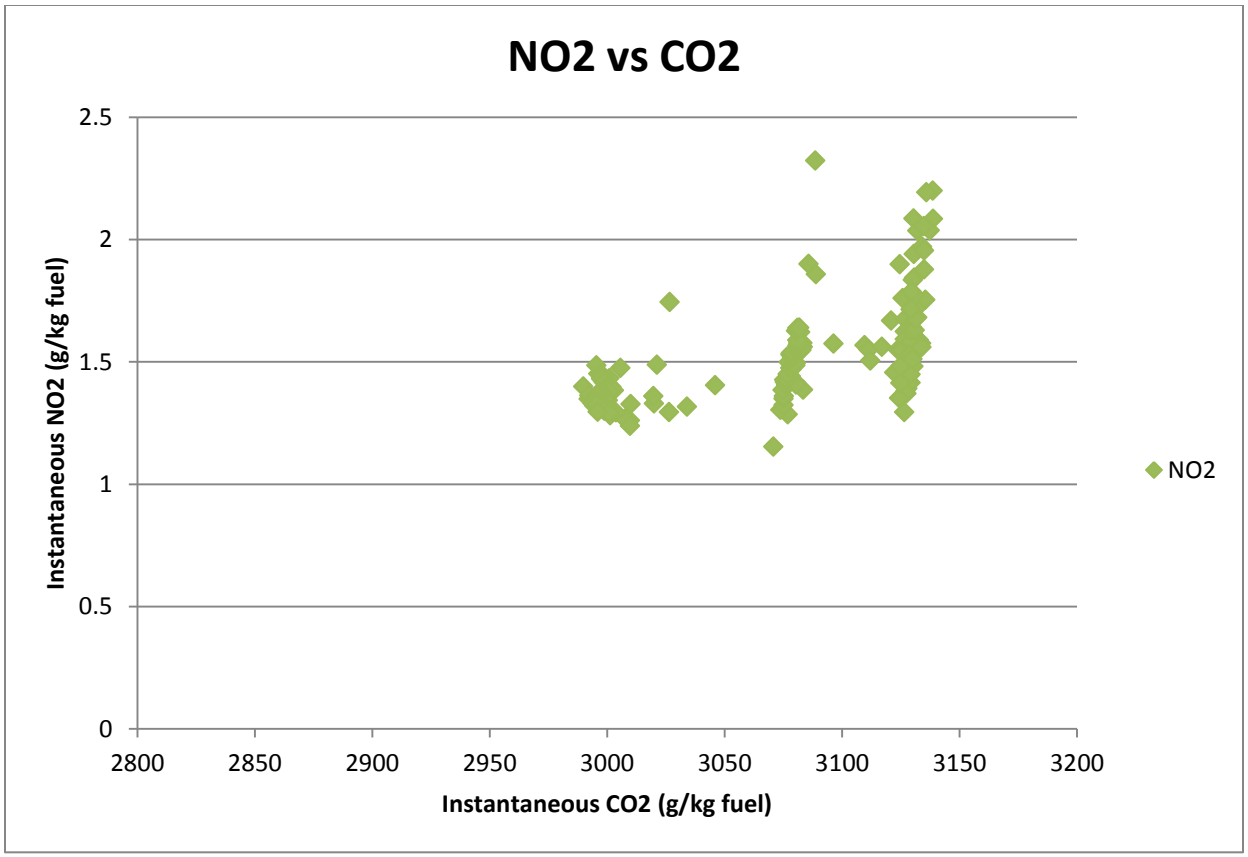

HC
Instantaneous HC (g/kg fuel)
0
5
10
15
20
25
30
35
40
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
HC

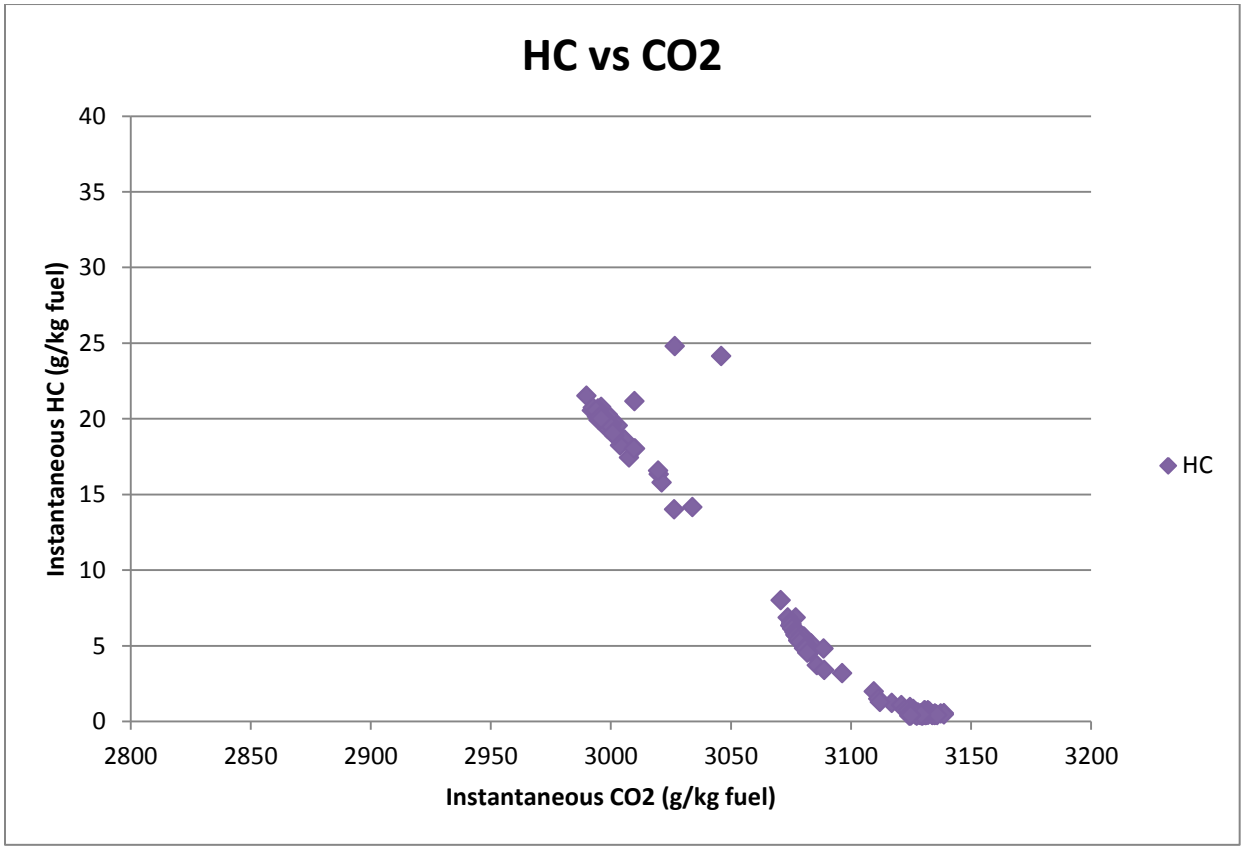

EGT
600
500
400
300
200
100
0
degrees C
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
EGT


O2
60000
50000
40000
30000
20000
10000
0
Instantaneous O2 (g/kg fuel)
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
O2

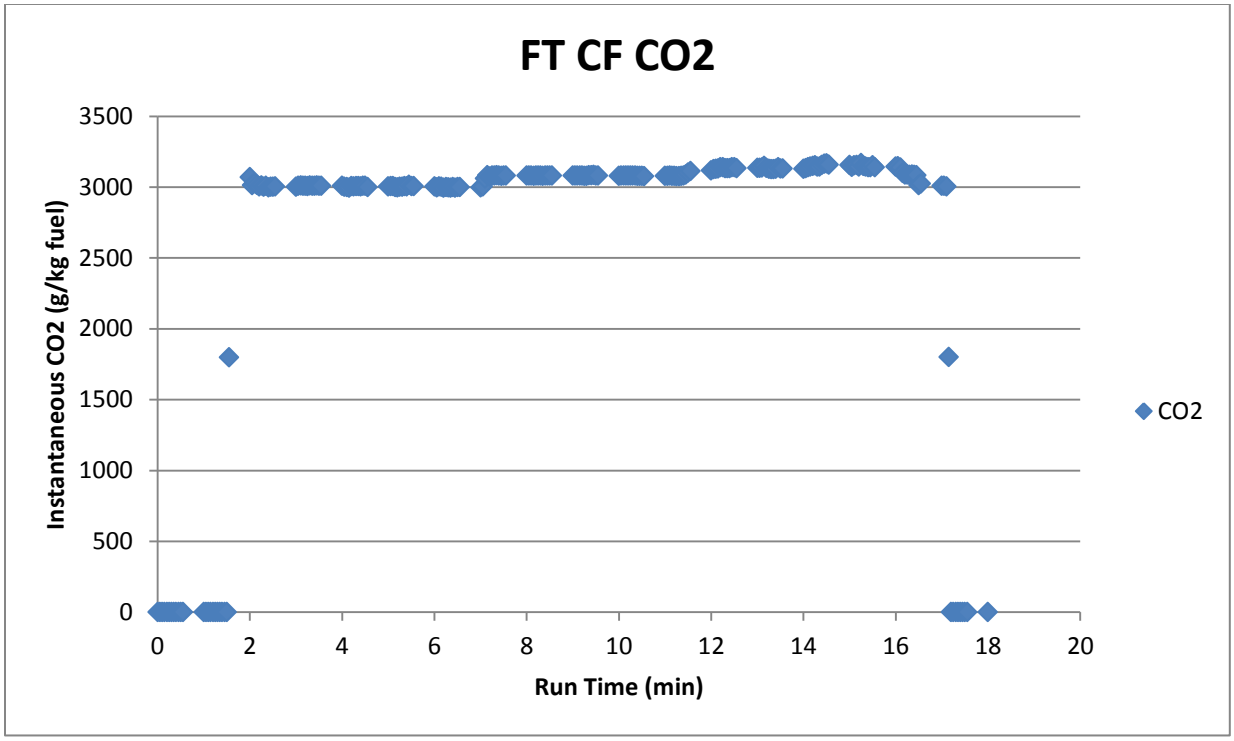

Instantaneous FT NCF CO2
Instantaneous CO2 (g/kg fuel)
3200
3150
3100
3050
3000
2950
2900
2850
2800
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
CO2

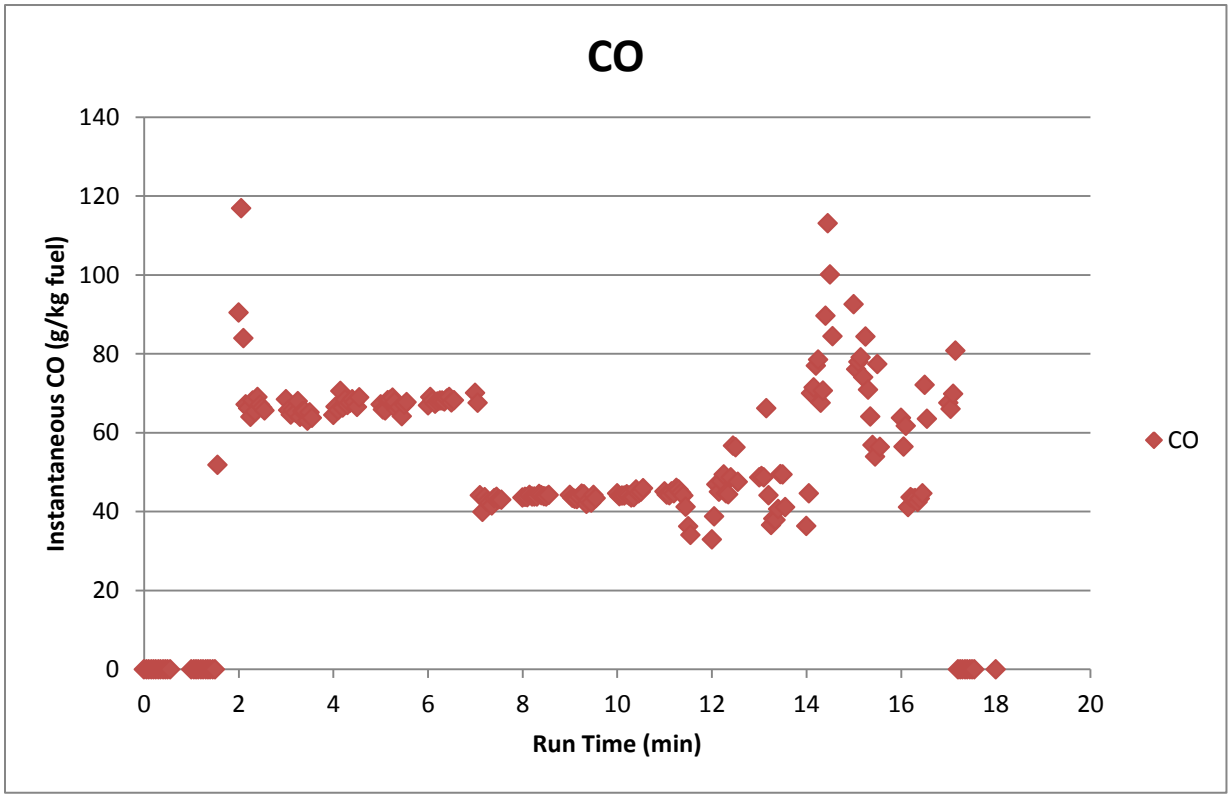

CO vs CO2
Instantaneous CO (g/kg fuel)
120
100
80
60
40
20
0
2800
2850
2900
2950
3000
3050
3100
3150
3200
Instantaneous CO2 (g/kg fuel)
CO

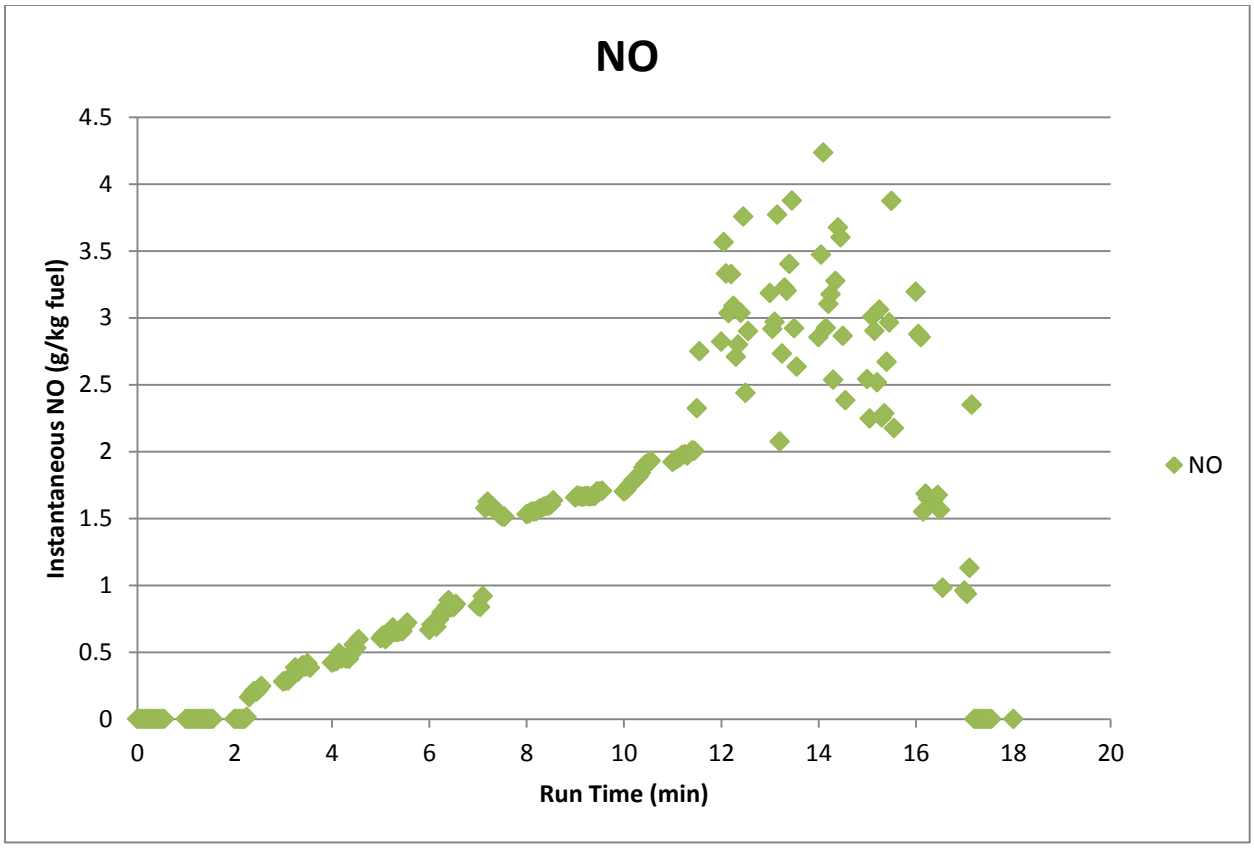

NO2 vs CO2
Instantaneous NO2 (g/kg fuel)
2.5
2
1.5
1
0.5
0
2800
2850
2900
2950
3000
3050
3100
3150
3200
Instantaneous CO2 (g/kg fuel)
NO2

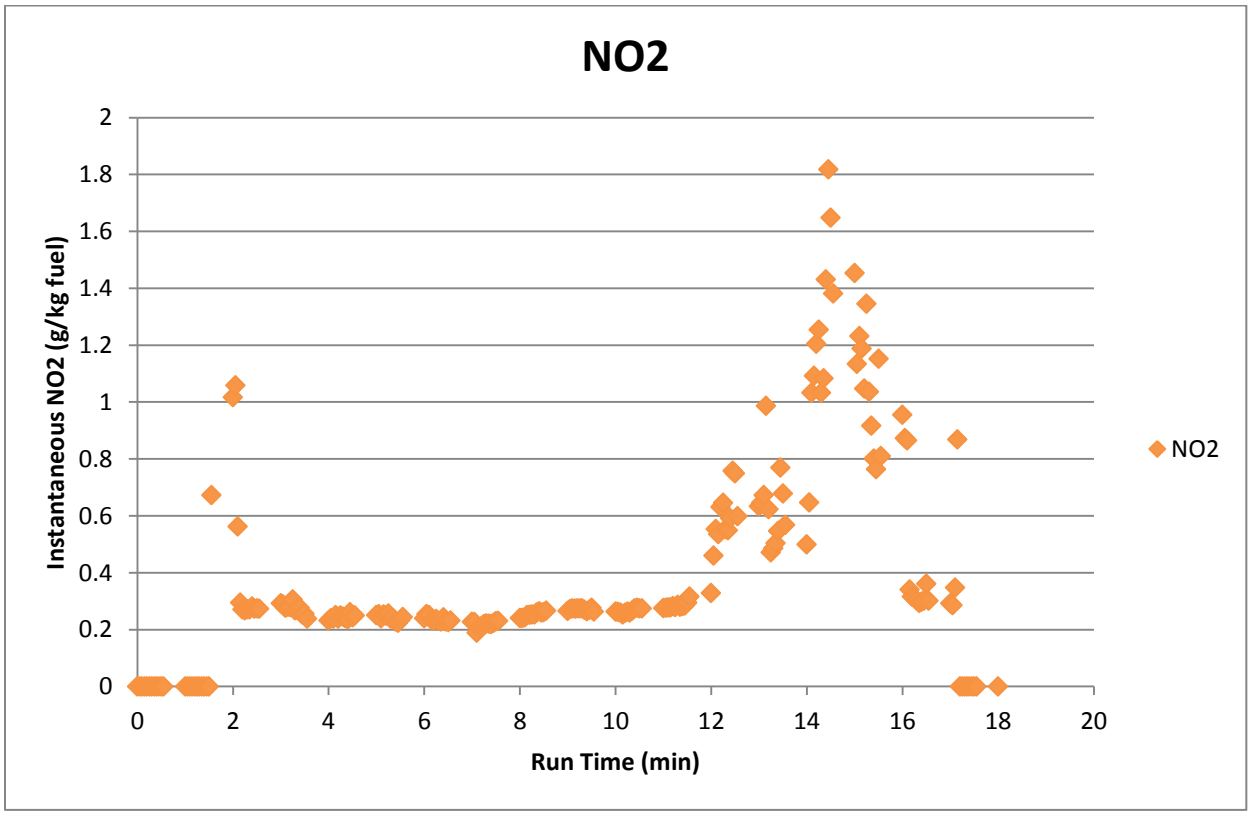

HC vs CO2
Instantaneous HC (g/kg fuel)
40
35
30
25
20
15
10
5
0
2800
2850
2900
2950
3000
3050
3100
3150
3200
Instantaneous CO2 (g/kg fuel)
HC

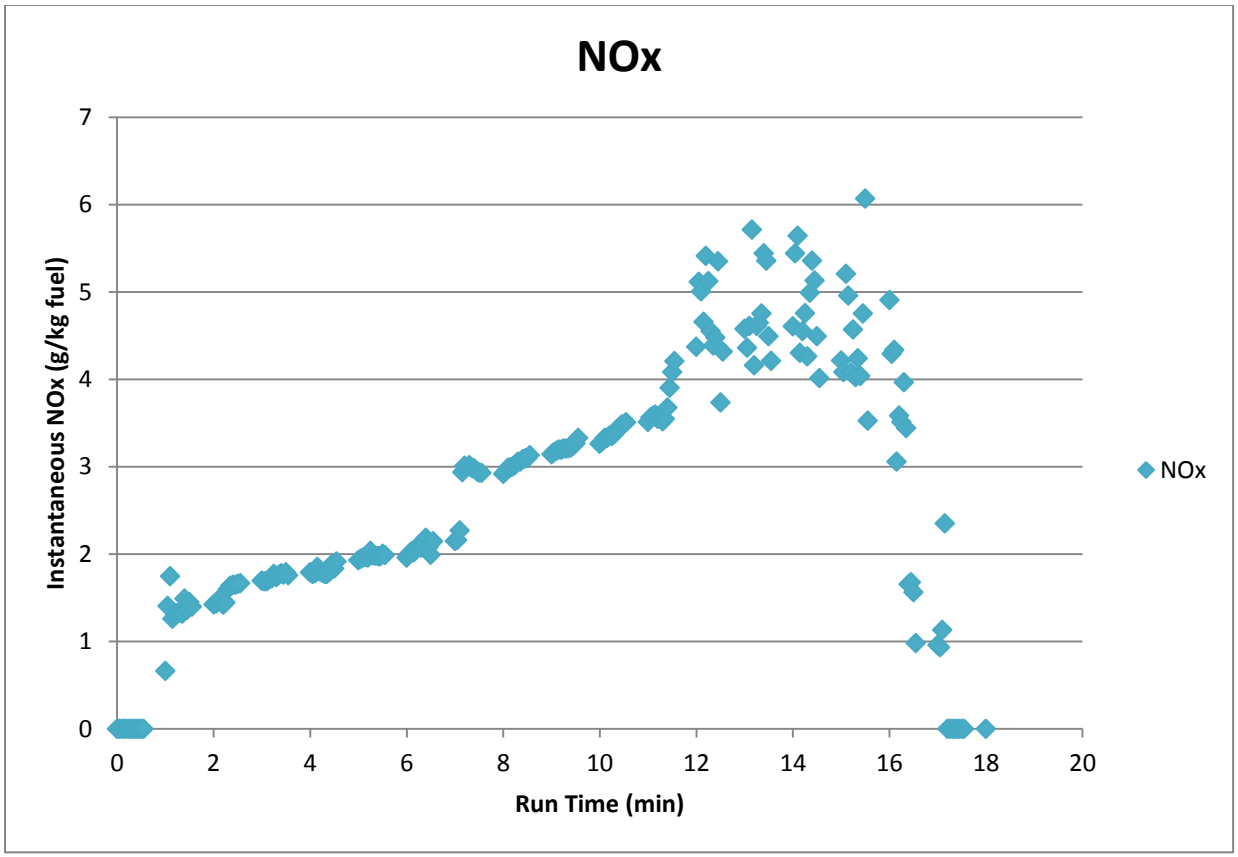
Salina3 HRJ CF 9/12/2012 PT6

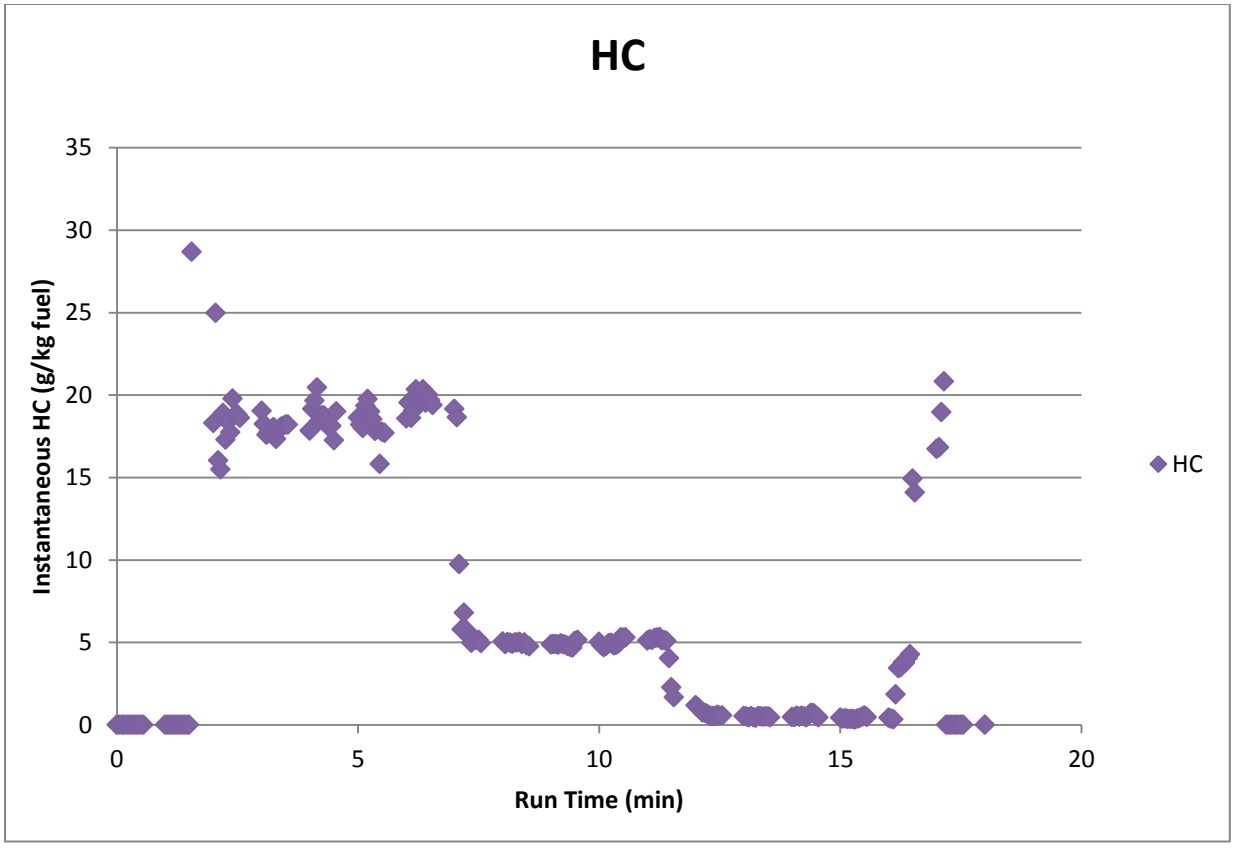


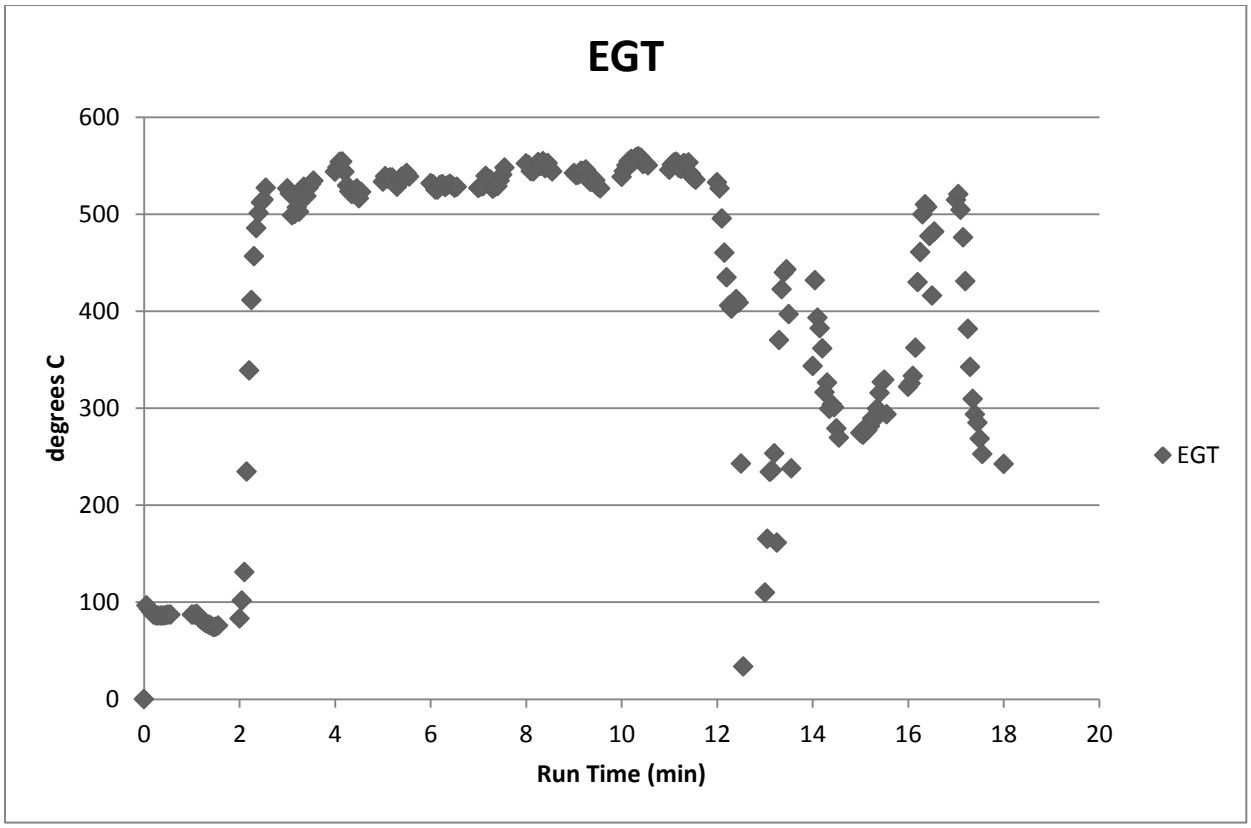


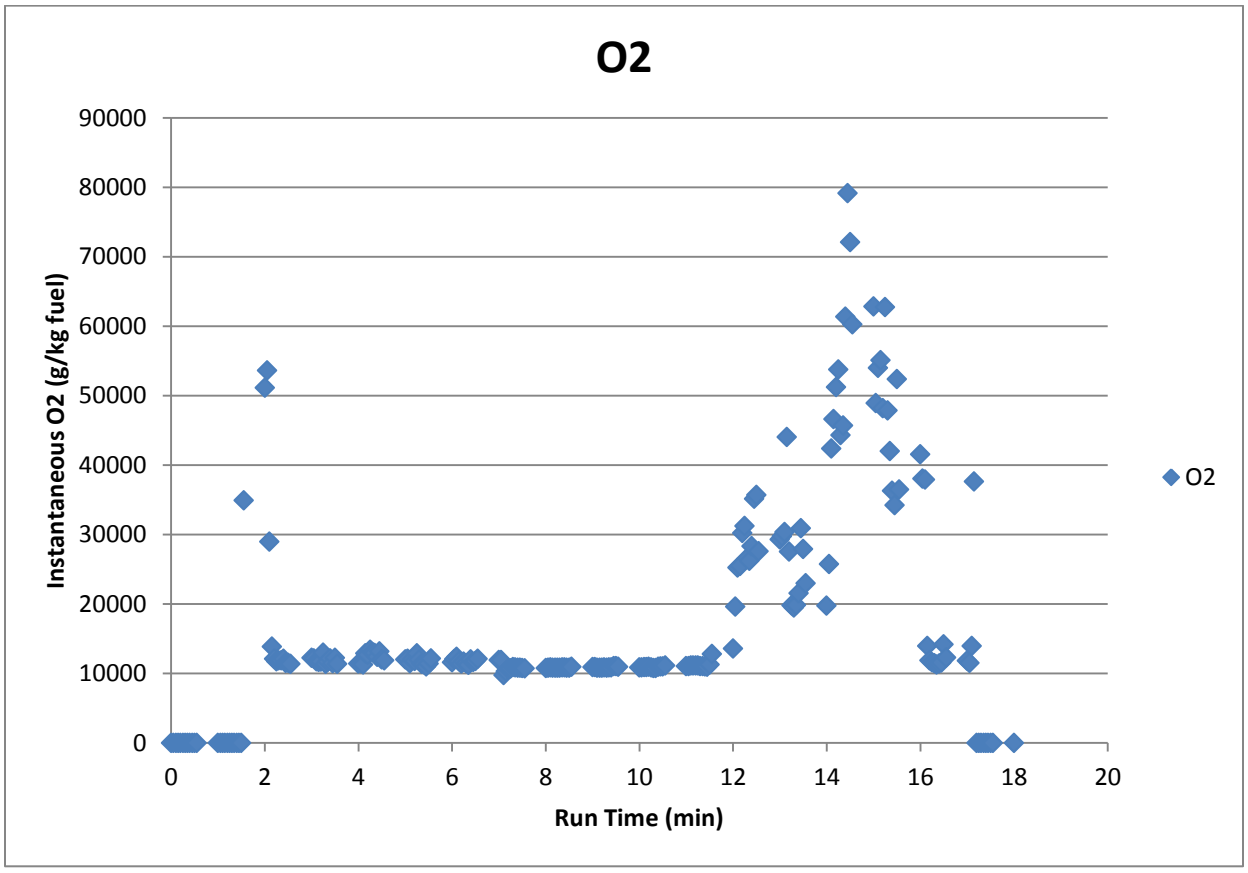

NO
Instantaneous NO (g/kg fuel)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
NO

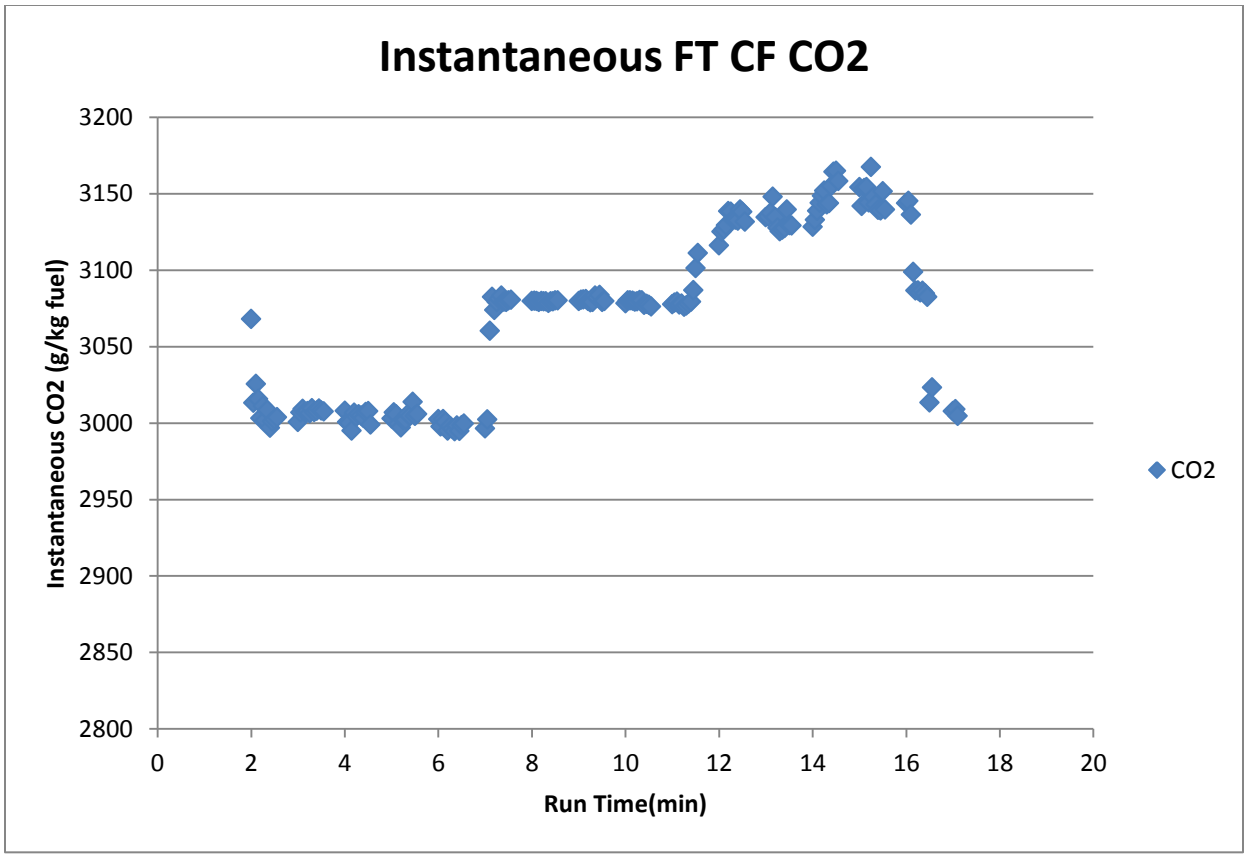

NO2
Instantaneous NO2 (g/kg fuel)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
NO2

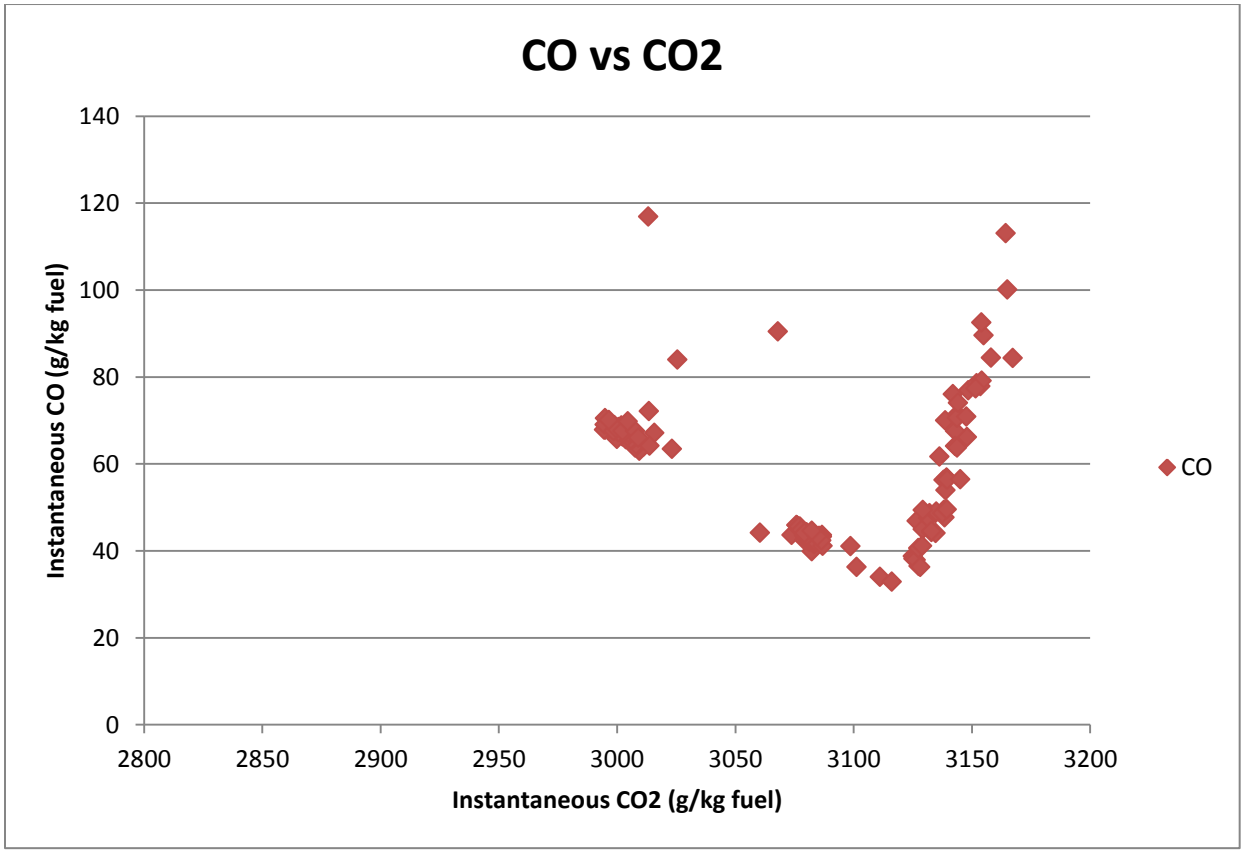

NOx
Instantaneous NOx (g/kg fuel)
0
1
2
3
4
5
6
7
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
NOx

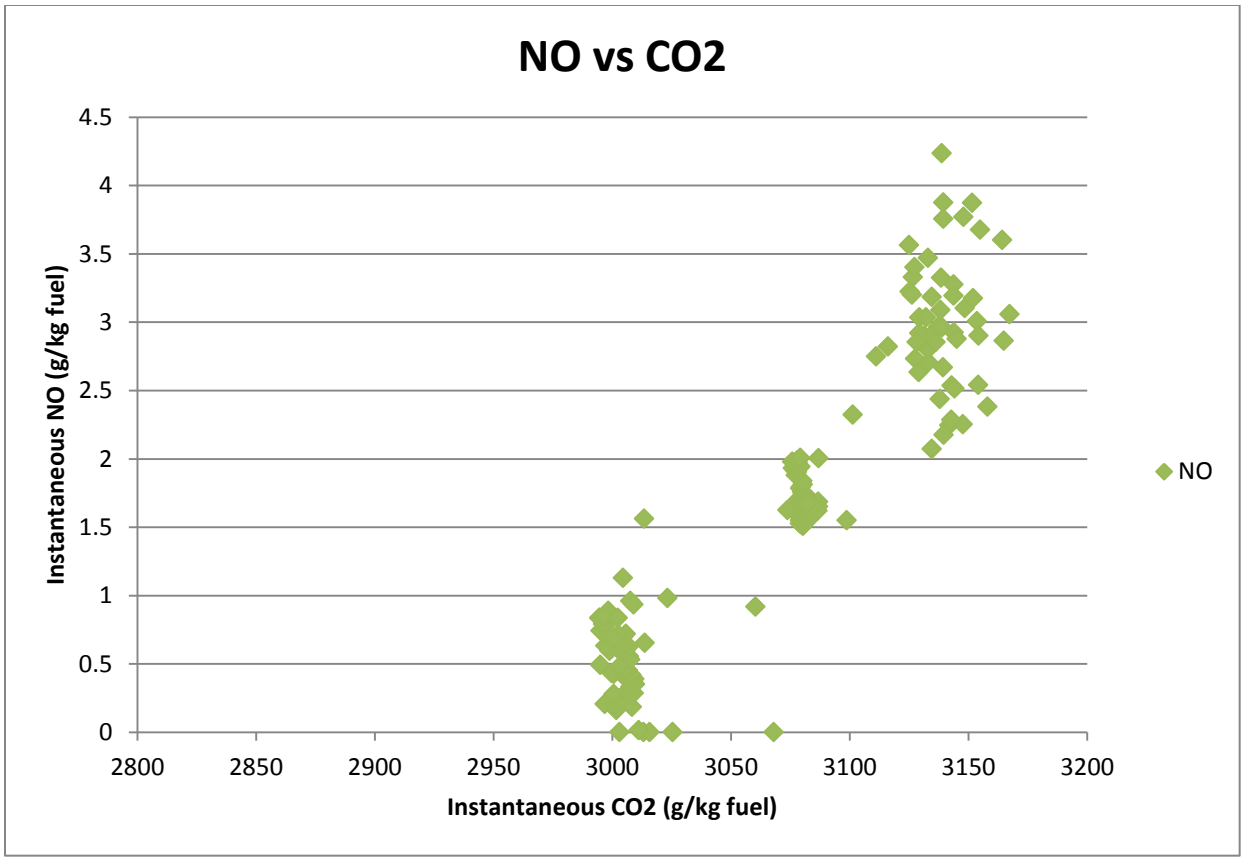

HC
Instantaneous HC (g/kg fuel)
0
5
10
15
20
25
30
35
0
5
10
15
20
Run Time (min)
HC

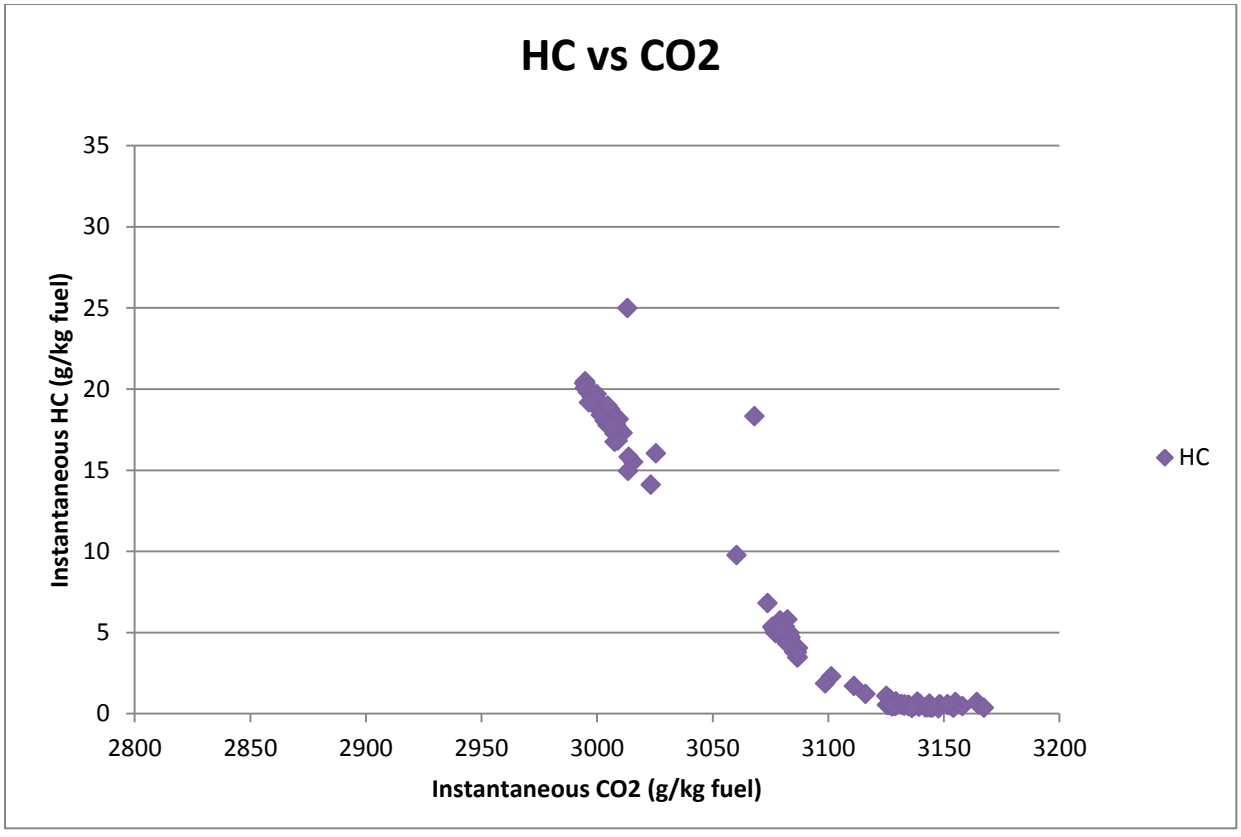

EGT
600
500
400
300
200
100
0
degrees C
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
EGT


O2
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
Instantaneous O2 (g/kg fuel)
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
O2

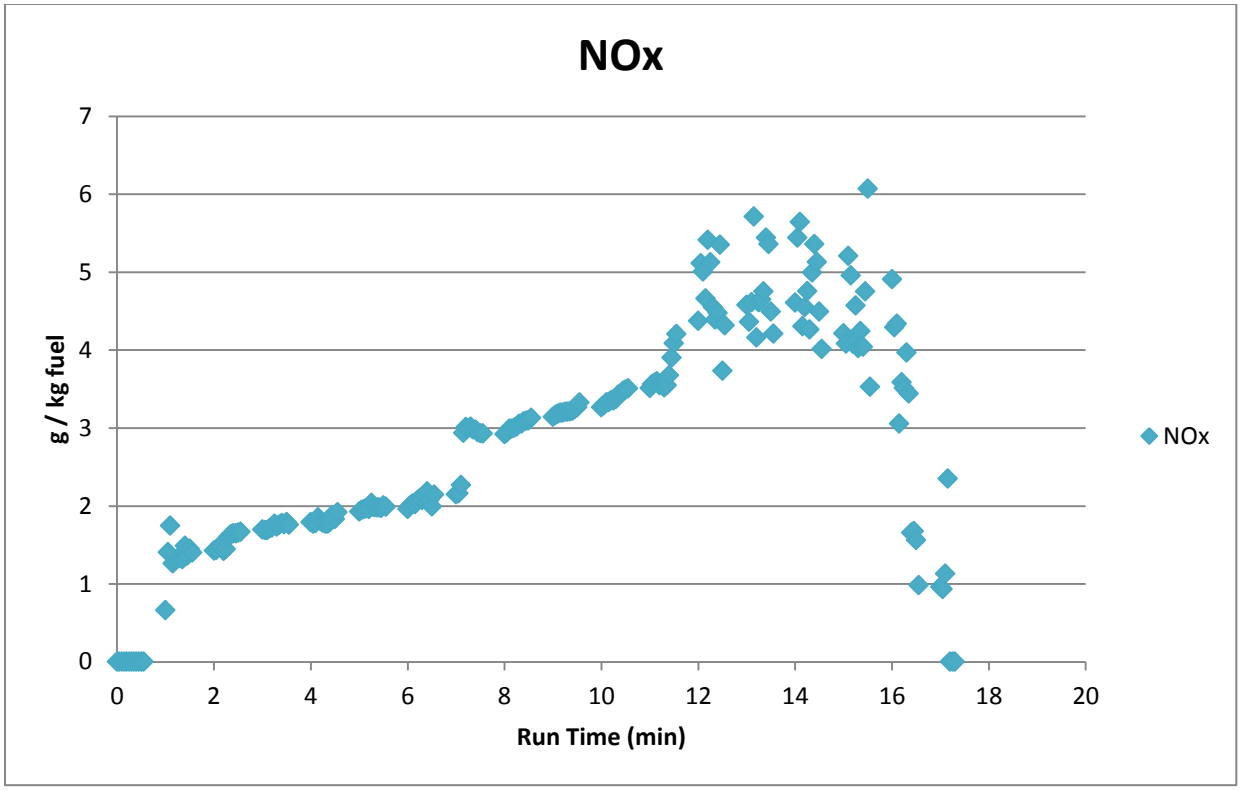

Instantaneous FT CF CO2
Instantaneous CO2 (g/kg fuel)
3200
3150
3100
3050
3000
2950
2900
2850
2800
0
2
4
6
8
10
12
14
16
18
20
Run Time(min)
CO2

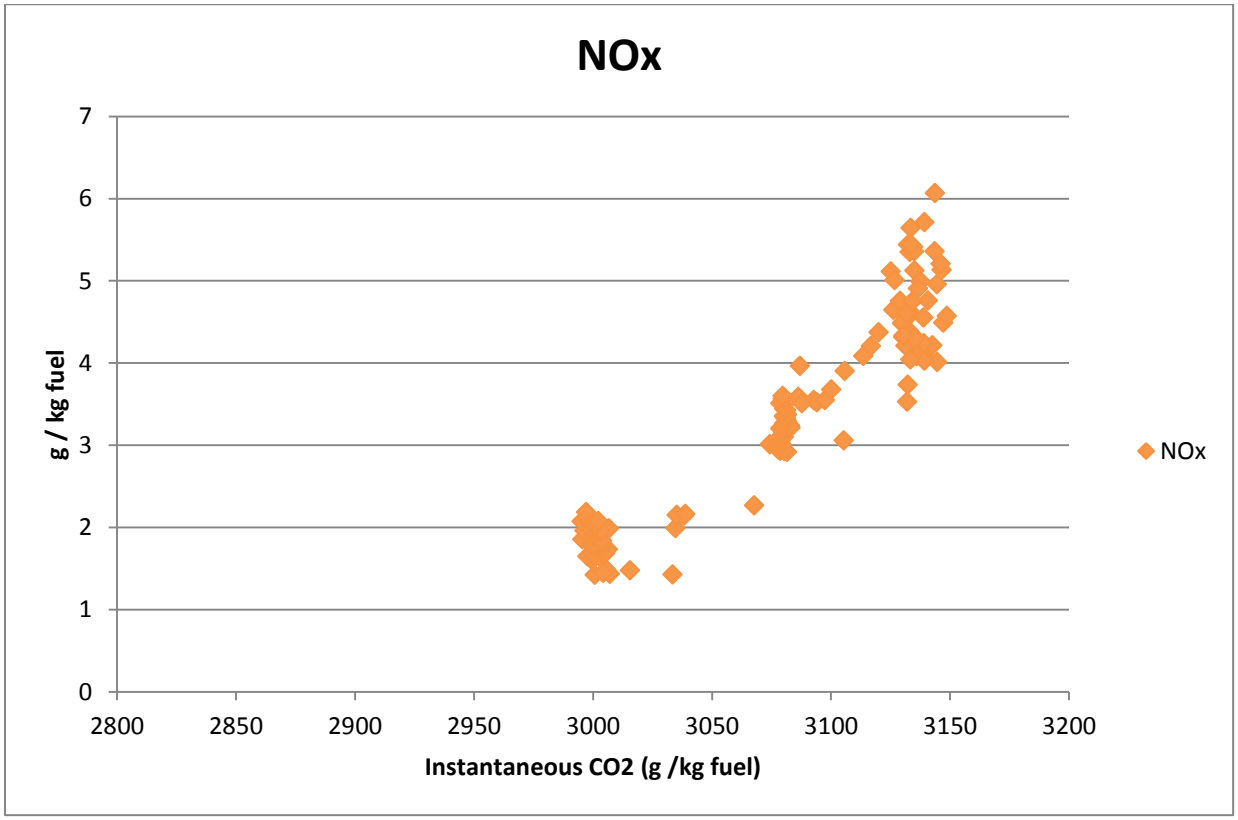

CO vs CO2
Instantaneous CO (g/kg fuel)
140
120
100
80
60
40
20
0
2800
2850
2900
2950
3000
3050
3100
3150
3200
Instantaneous CO2 (g/kg fuel)
CO


NO vs CO2
Instantaneous NO (g/kg fuel)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
2800
2850
2900
2950
3000
3050
3100
3150
3200
Instantaneous CO2 (g/kg fuel)
NO


HC vs CO2
Instantaneous HC (g/kg fuel)
35
30
25
20
15
10
5
0
2800
2850
2900
2950
3000
3050
3100
3150
3200
Instantaneous CO2 (g/kg fuel)
HC

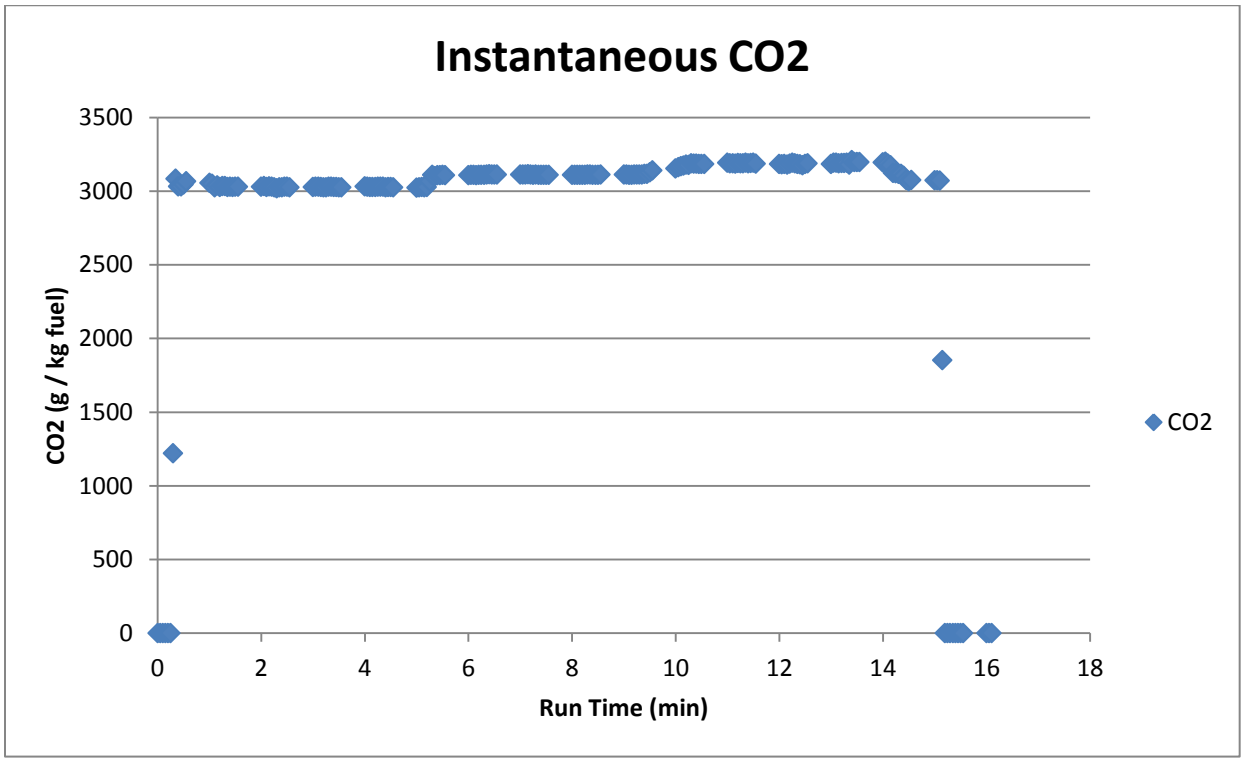
Salina3 FT Combined NOx 9/12/2012 PT6

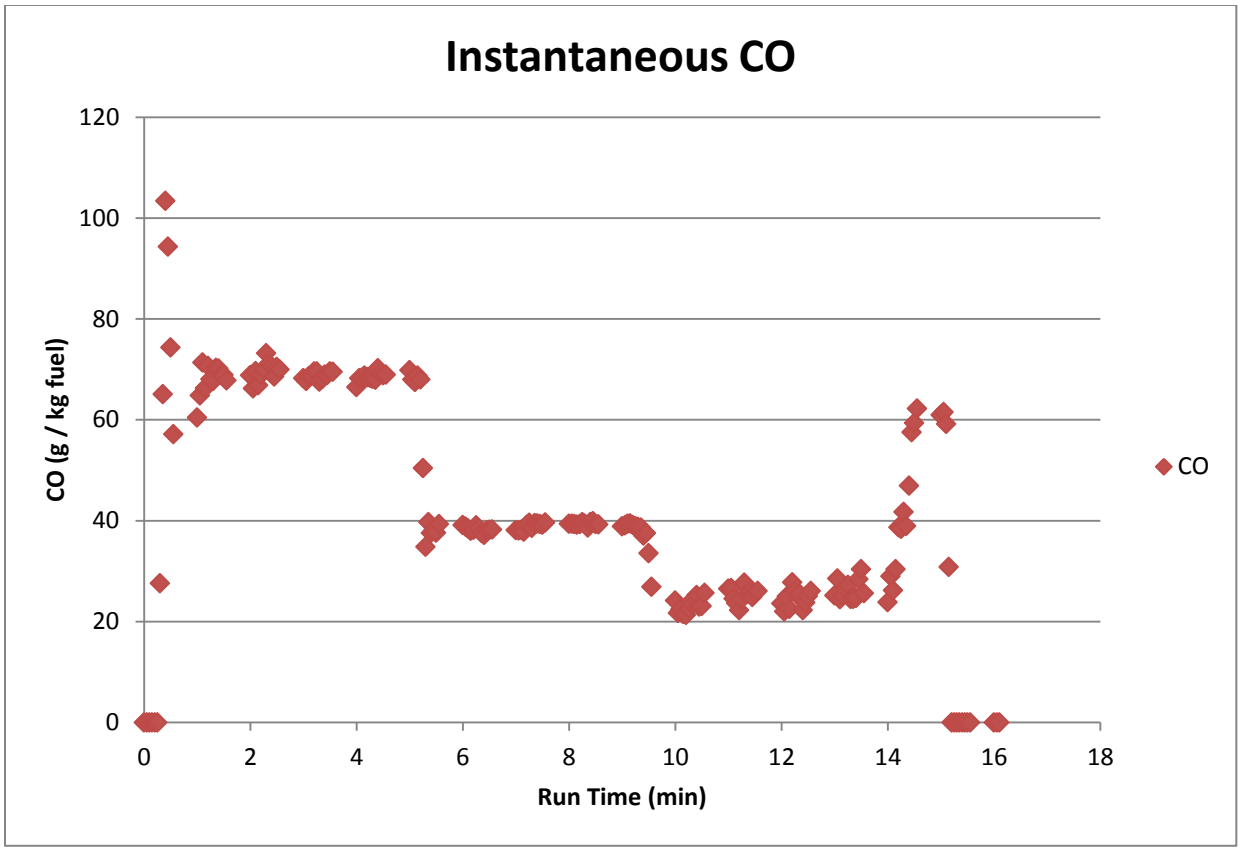


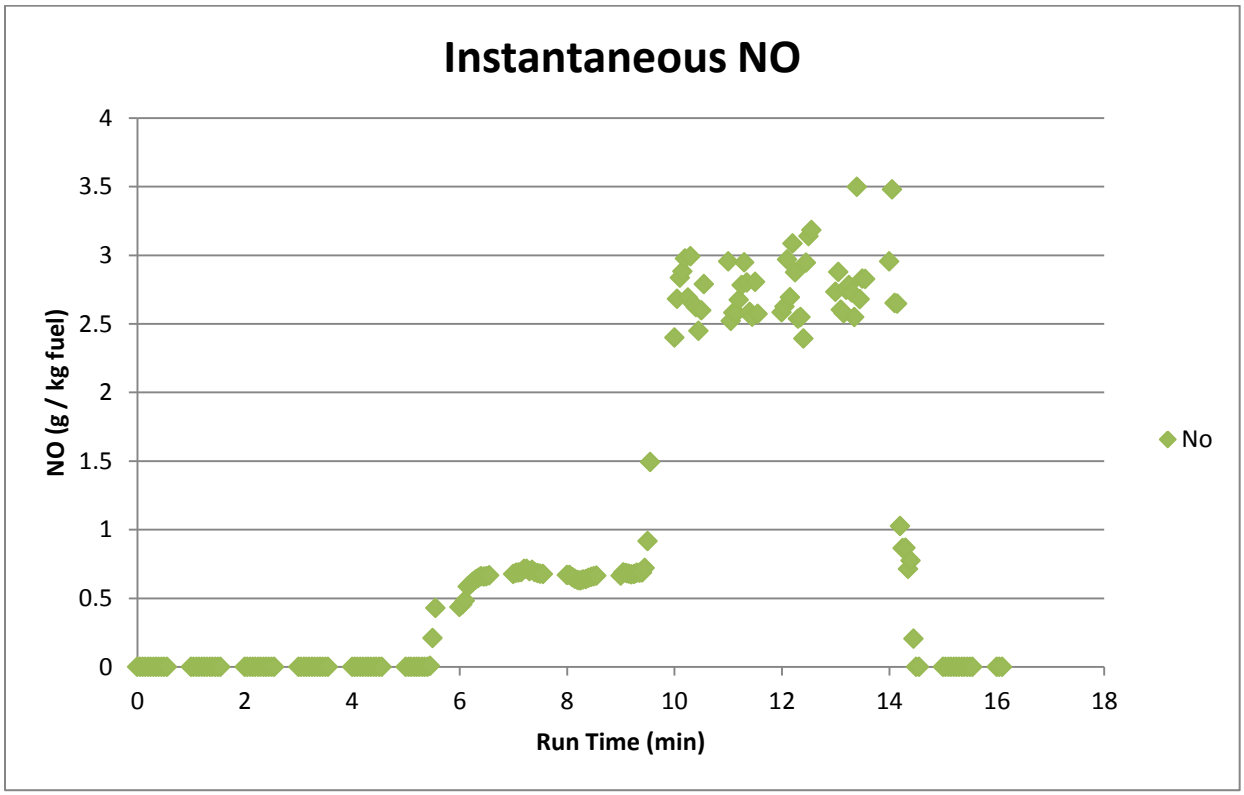


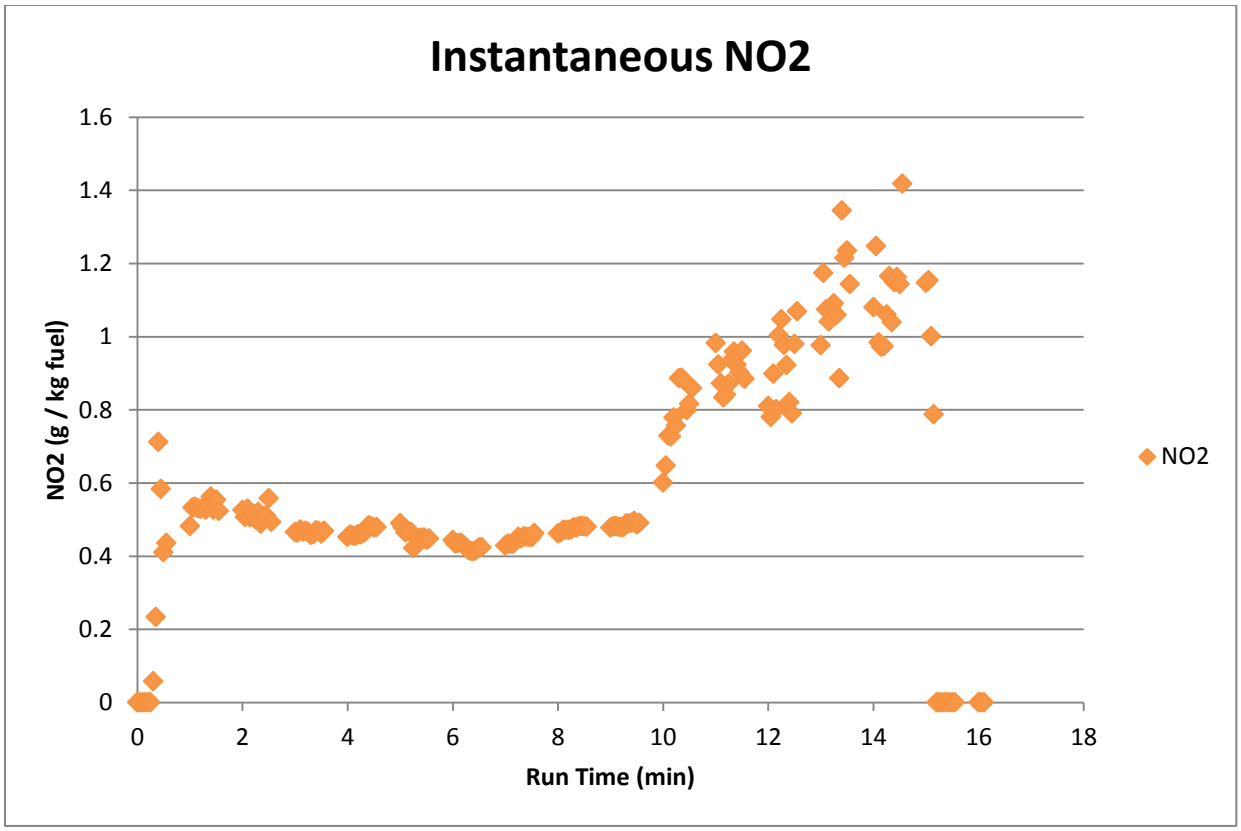
Appendix E: Results from 10/24/2012 Salina Sampling

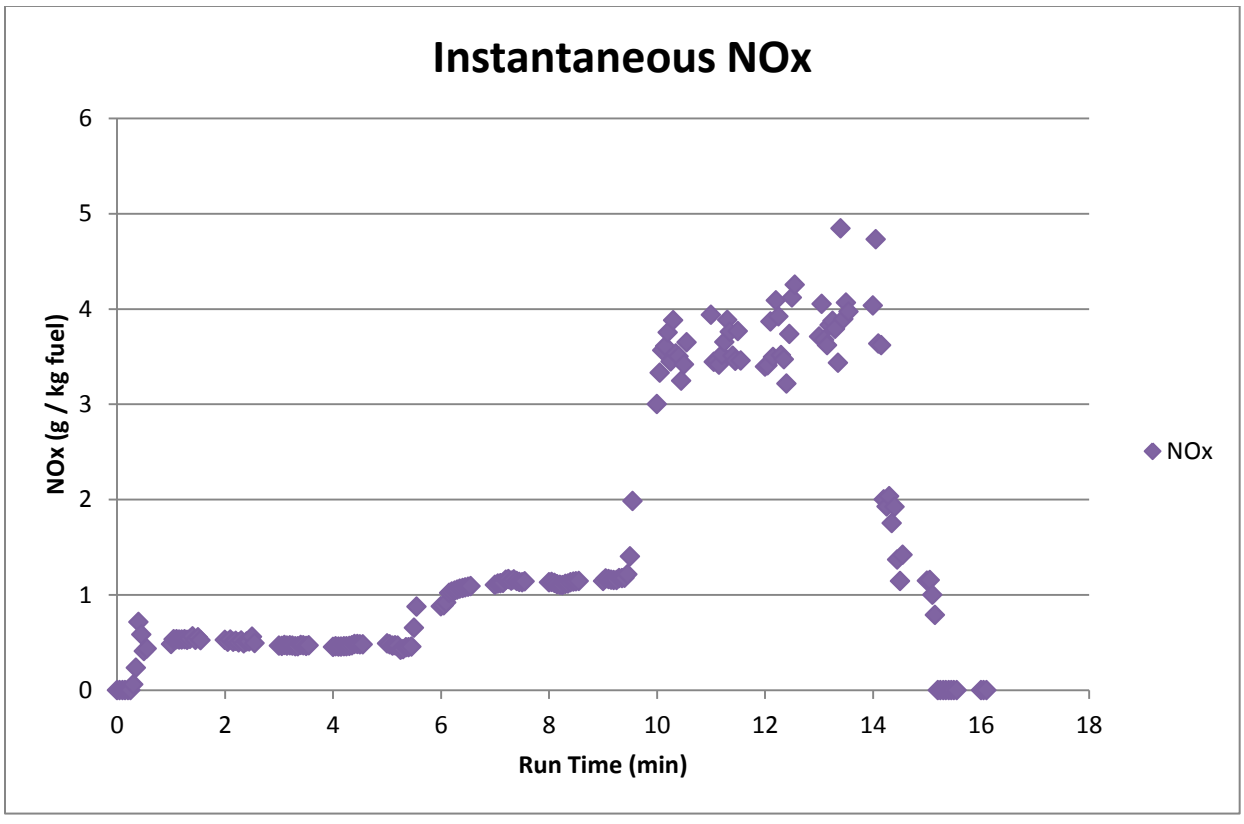
Salina4 Jet A NCF 10/24/2012 PT6

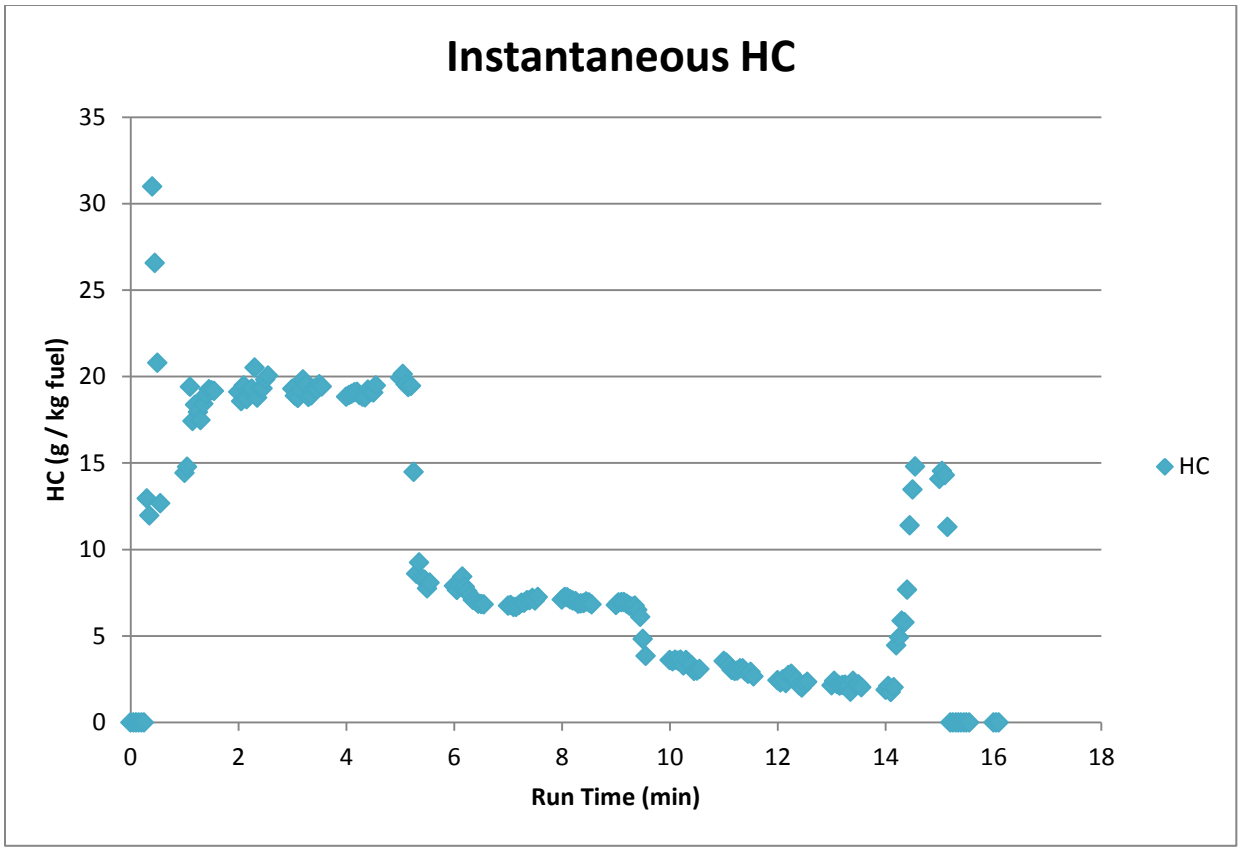


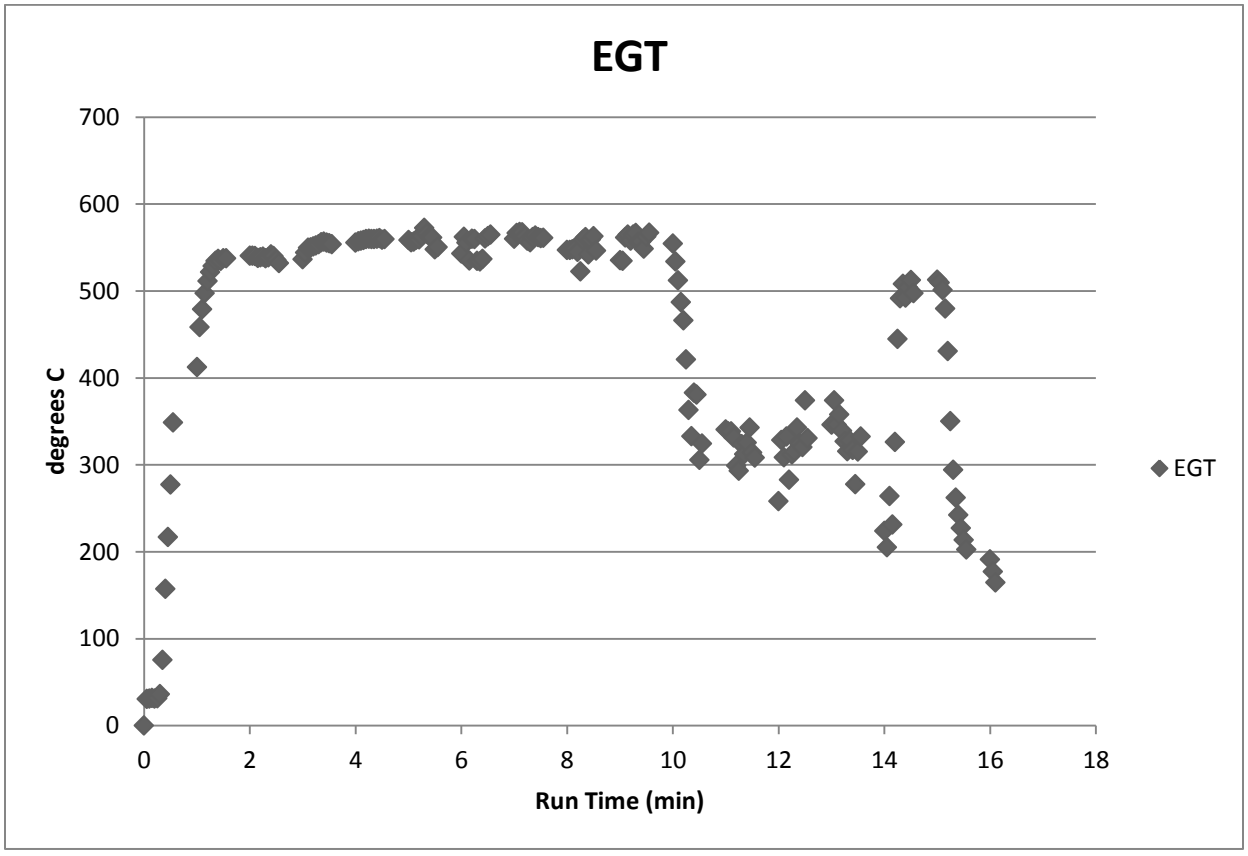

Instantaneous CO
CO (g / kg fuel)
120
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16
18
Run Time (min)
CO

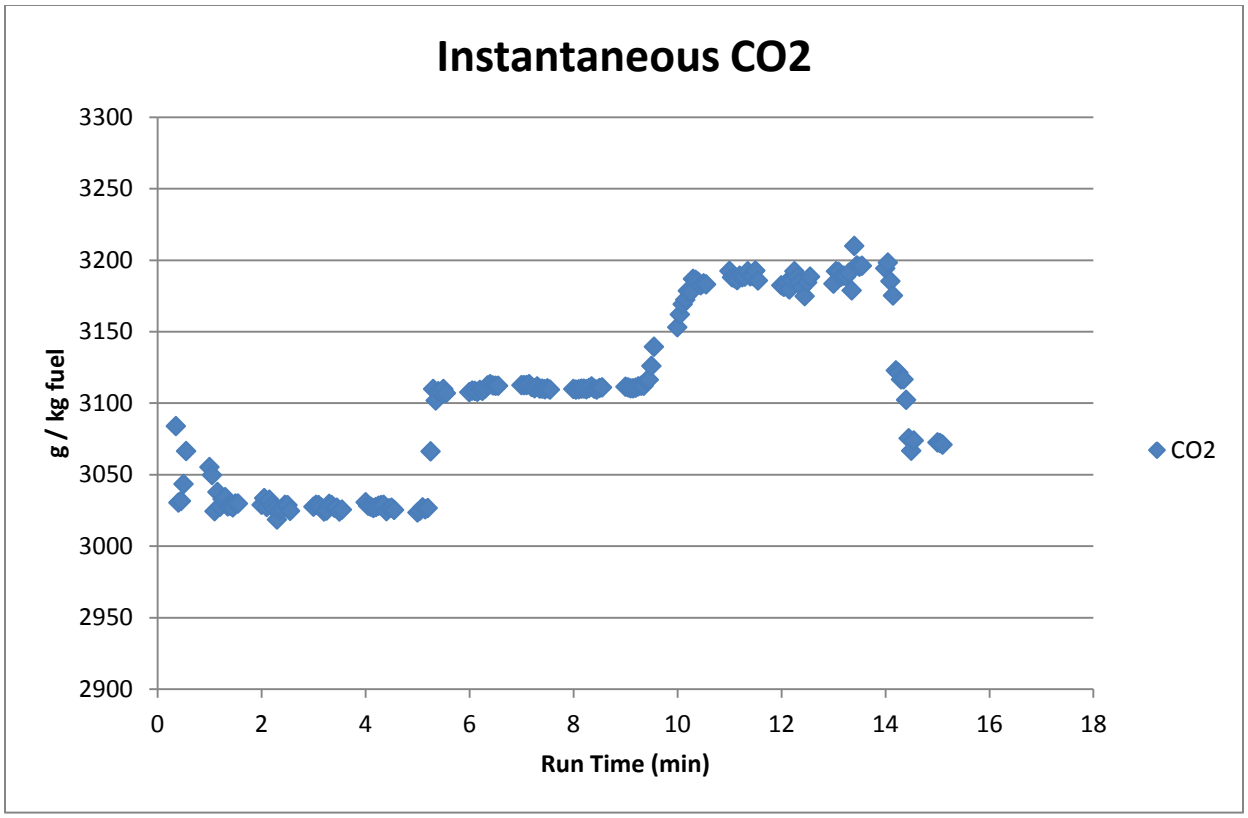

Instantaneous NO
NO (g / kg fuel)
4
3.5
3
2.5
2
1.5
1
0.5
0
0
2
4
6
8
10
12
14
16
18
Run Time (min)
No

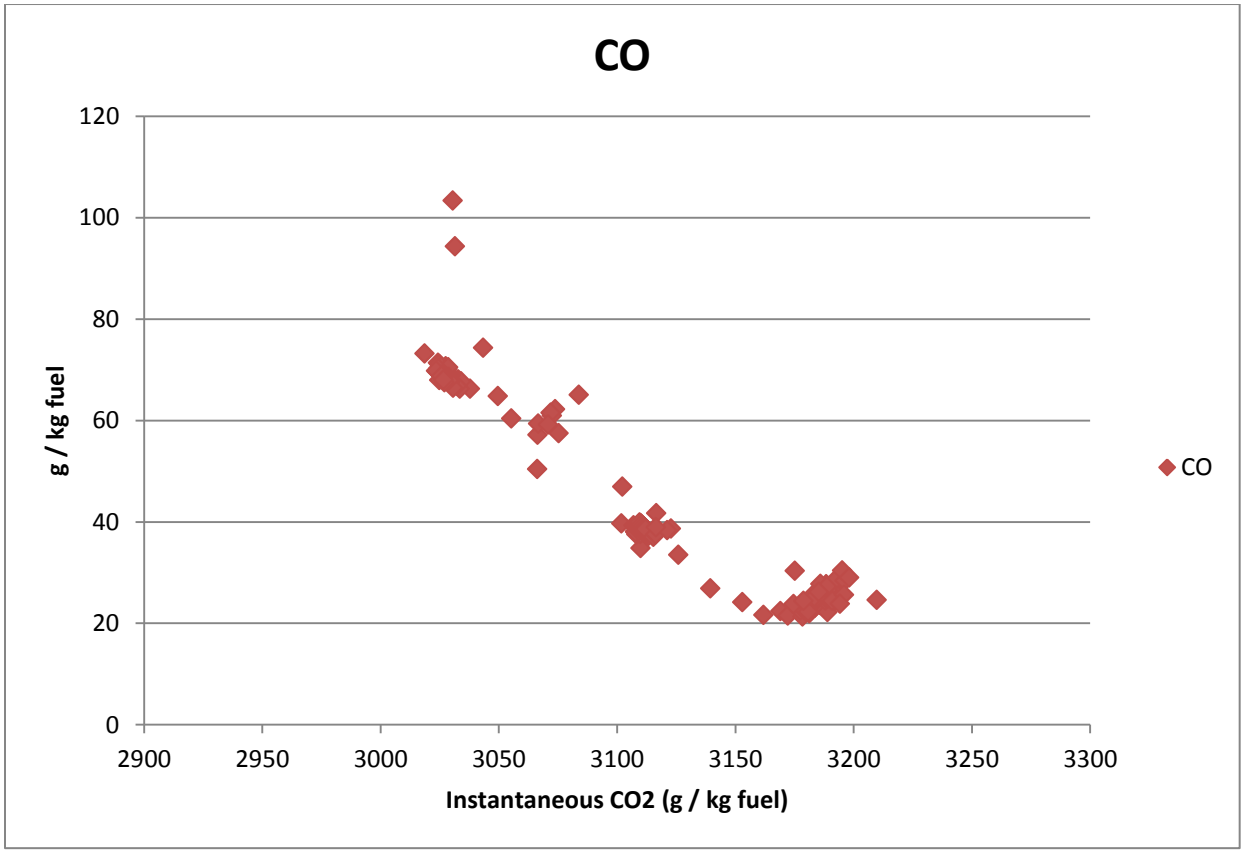

Instantaneous NO2
NO2 (g / kg fuel)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
2
4
6
8
10
12
14
16
18
Run Time (min)
NO2

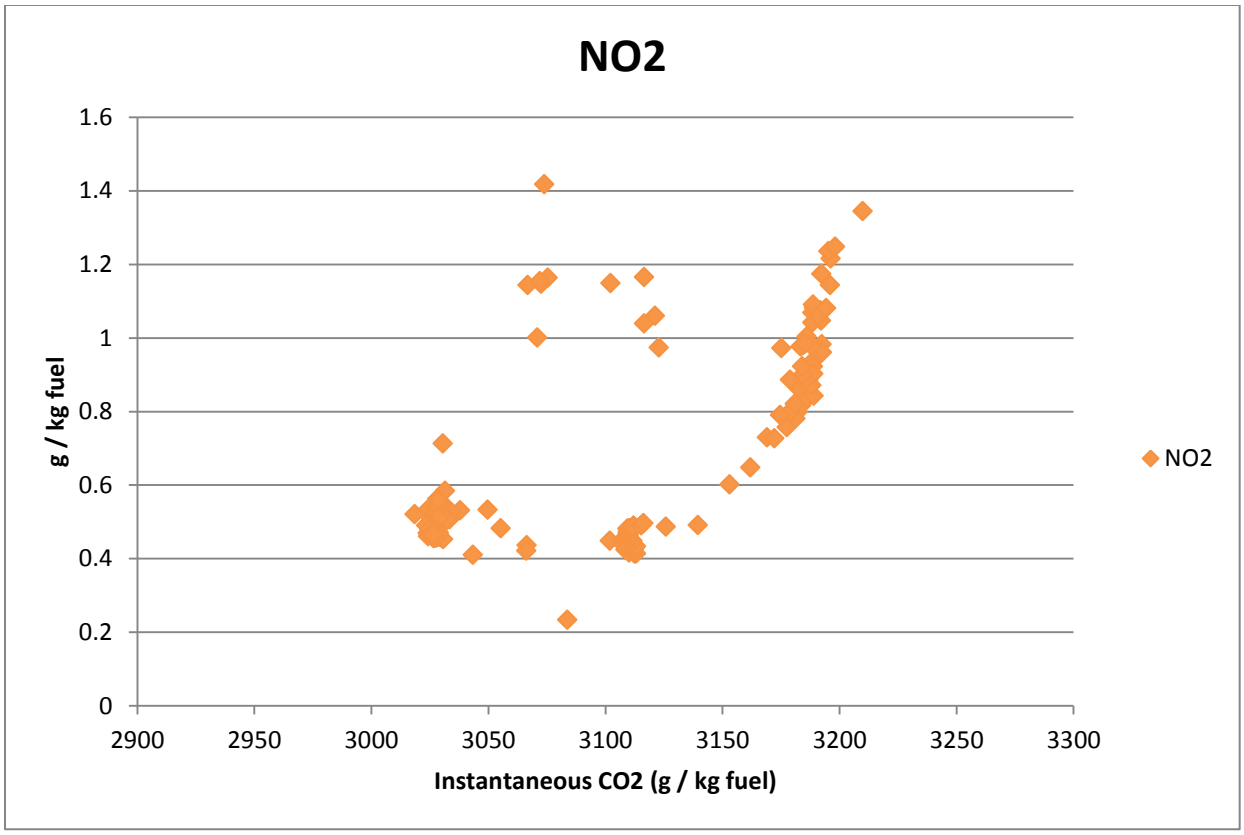

Instantaneous NOx
NOx (g / kg fuel)
6
5
4
3
2
1
0
0
2
4
6
8
10
12
14
16
18
Run Time (min)
NOx

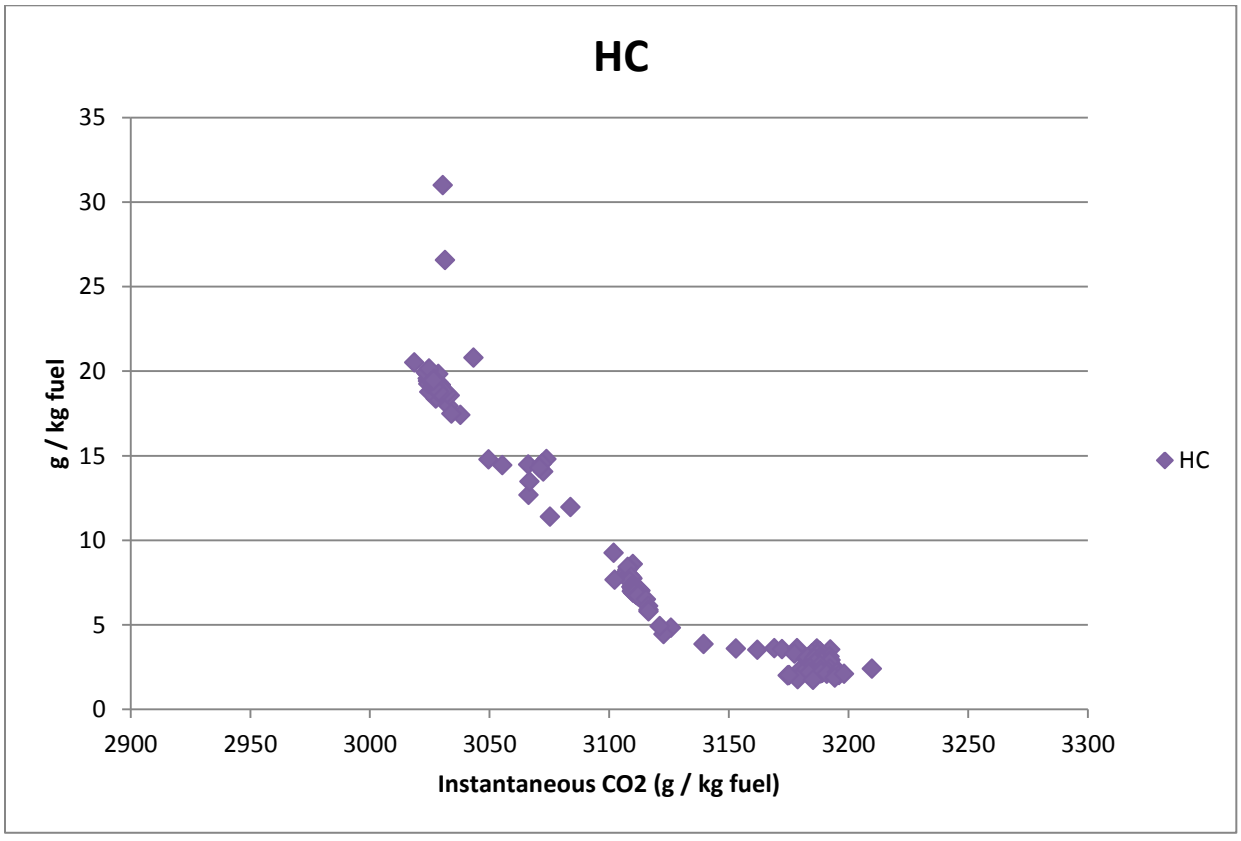

Instantaneous HC
HC (g / kg fuel)
35
30
25
20
15
10
5
0
0
2
4
6
8
10
12
14
16
18
Run Time (min)
HC


EGT
degrees C
700
600
500
400
300
200
100
0
0
2
4
6
8
10
12
14
16
18
Run Time (min)
EGT

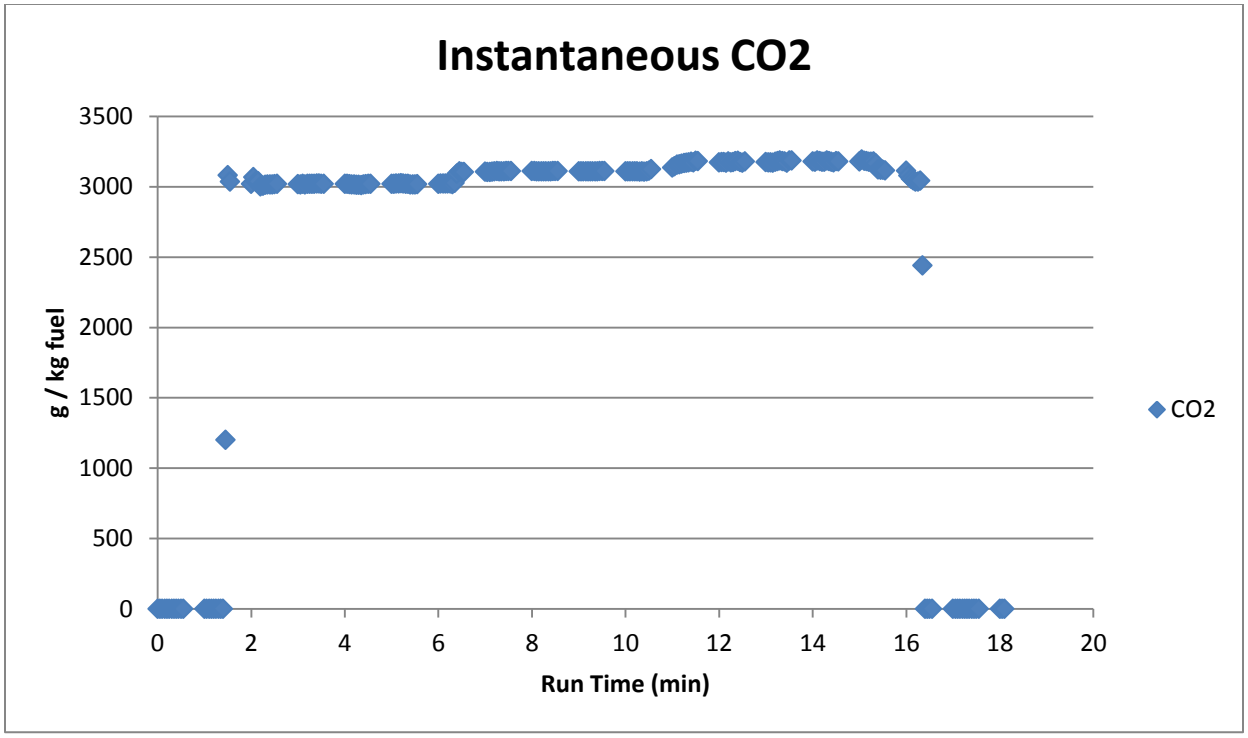

Instantaneous CO2
3300
3250
3200
3150
3100
3050
3000
2950
2900
g / kg fuel
0
2
4
6
8
10
12
14
16
18
Run Time (min)
CO2

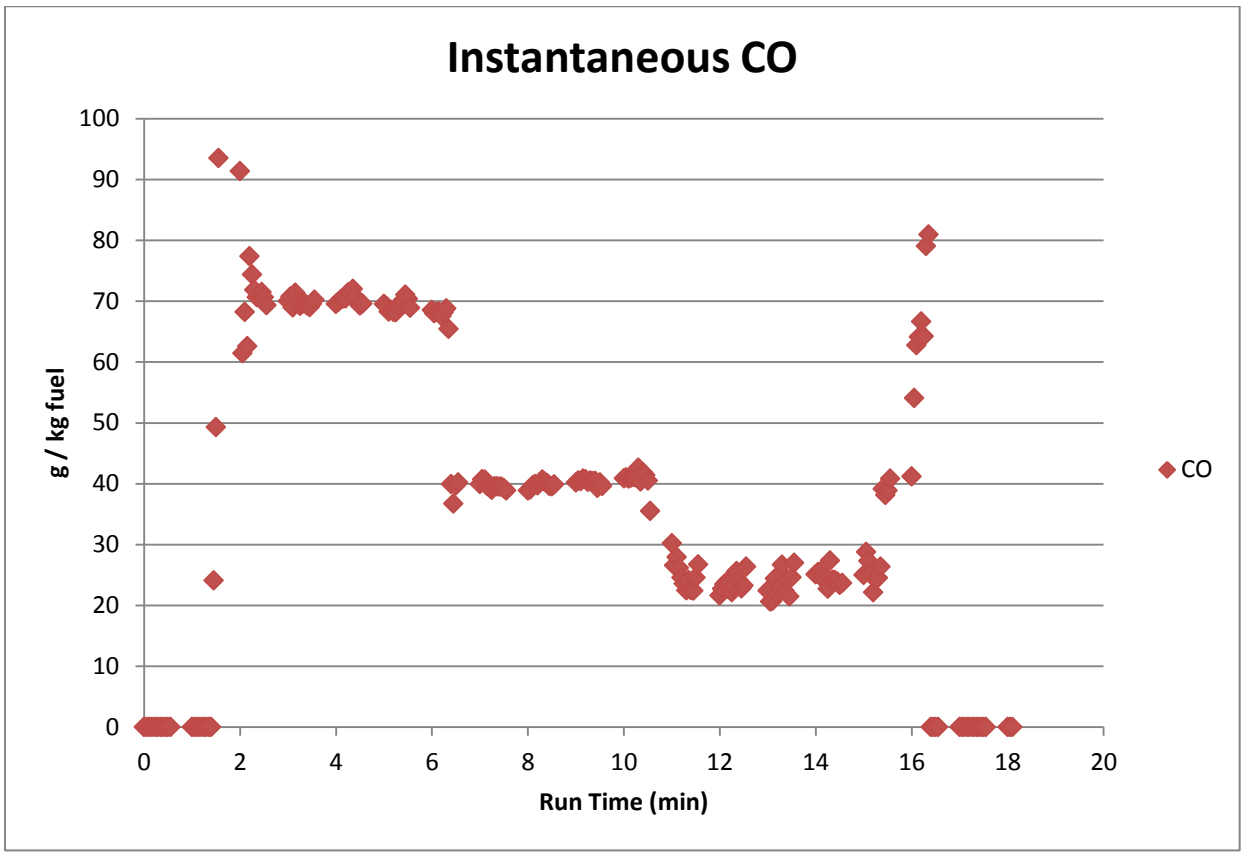

CO
120
100
80
60
40
20
0
g / kg fuel
2900
2950
3000
3050
3100
3150
3200
3250
3300
Instantaneous CO2 (g / kg fuel)
CO

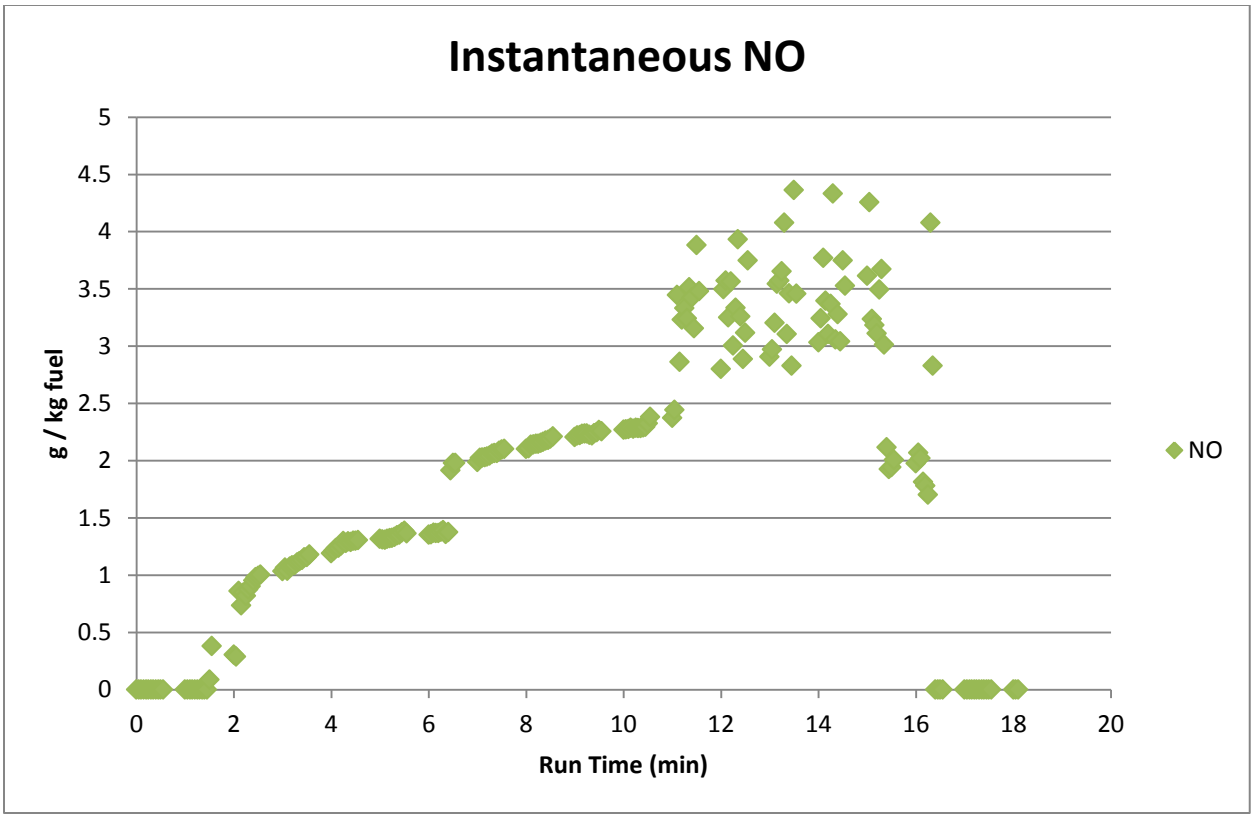

NO2
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
g / kg fuel
2900
2950
3000
3050
3100
3150
3200
3250
3300
Instantaneous CO2 (g / kg fuel)
NO2

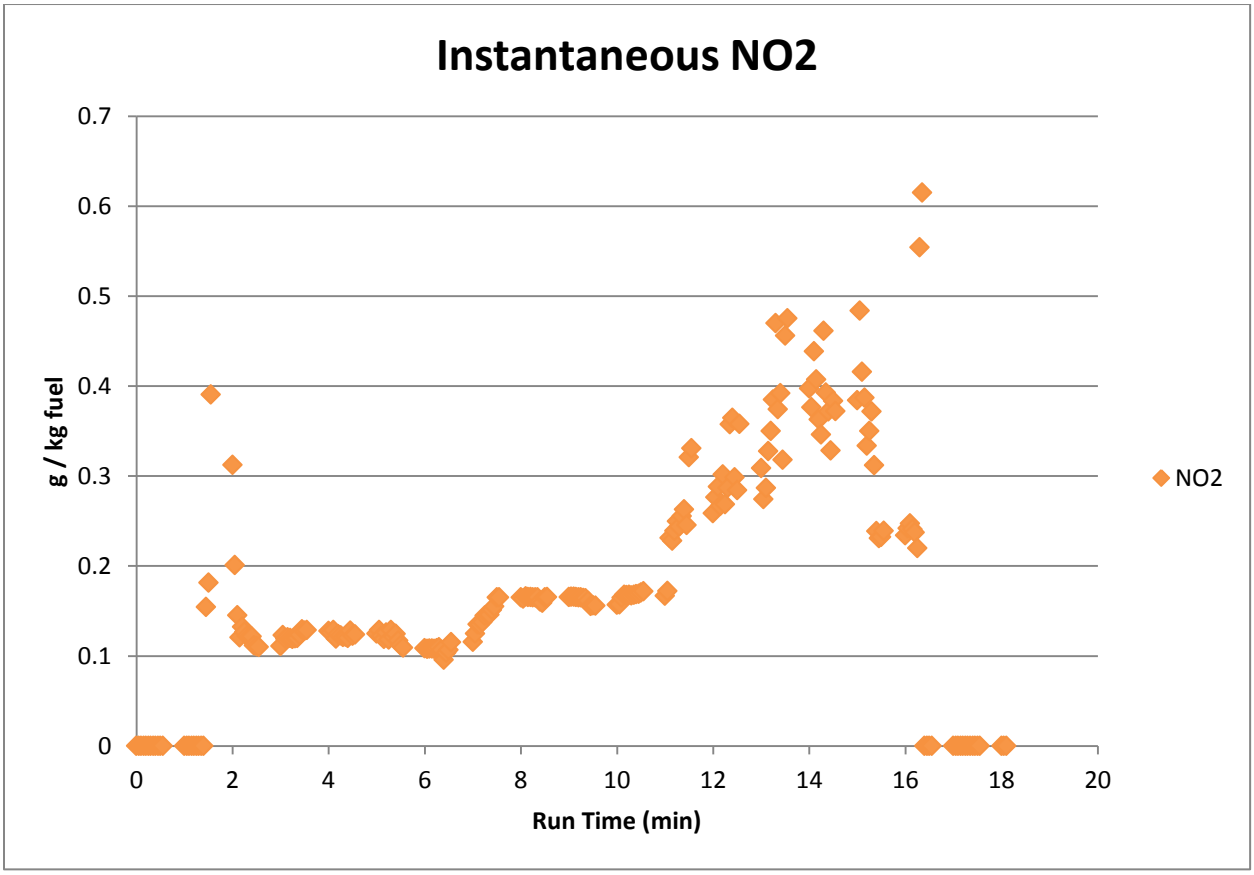

HC
35
30
25
20
15
10
5
0
g / kg fuel
2900
2950
3000
3050
3100
3150
3200
3250
3300
Instantaneous CO2 (g / kg fuel)
HC

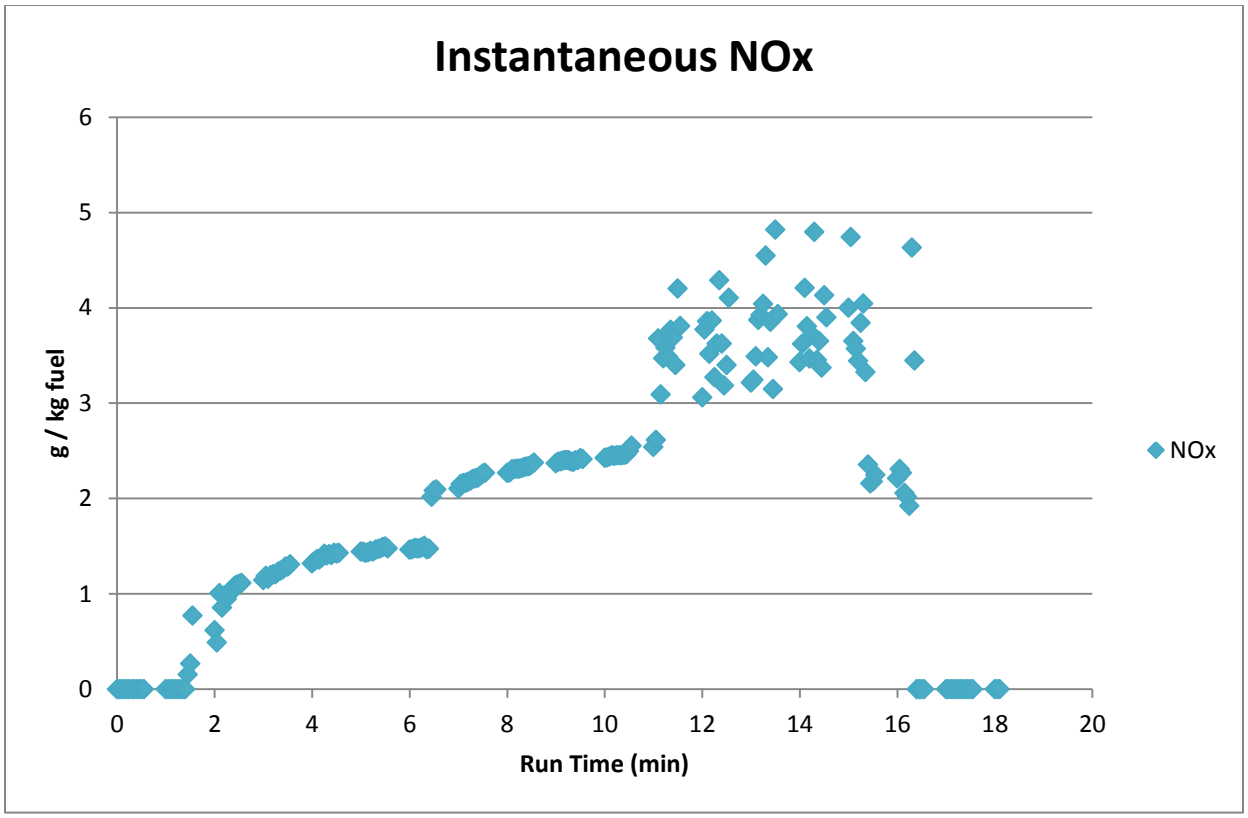
Salina4 Jet A CF 10/24/2012 PT6

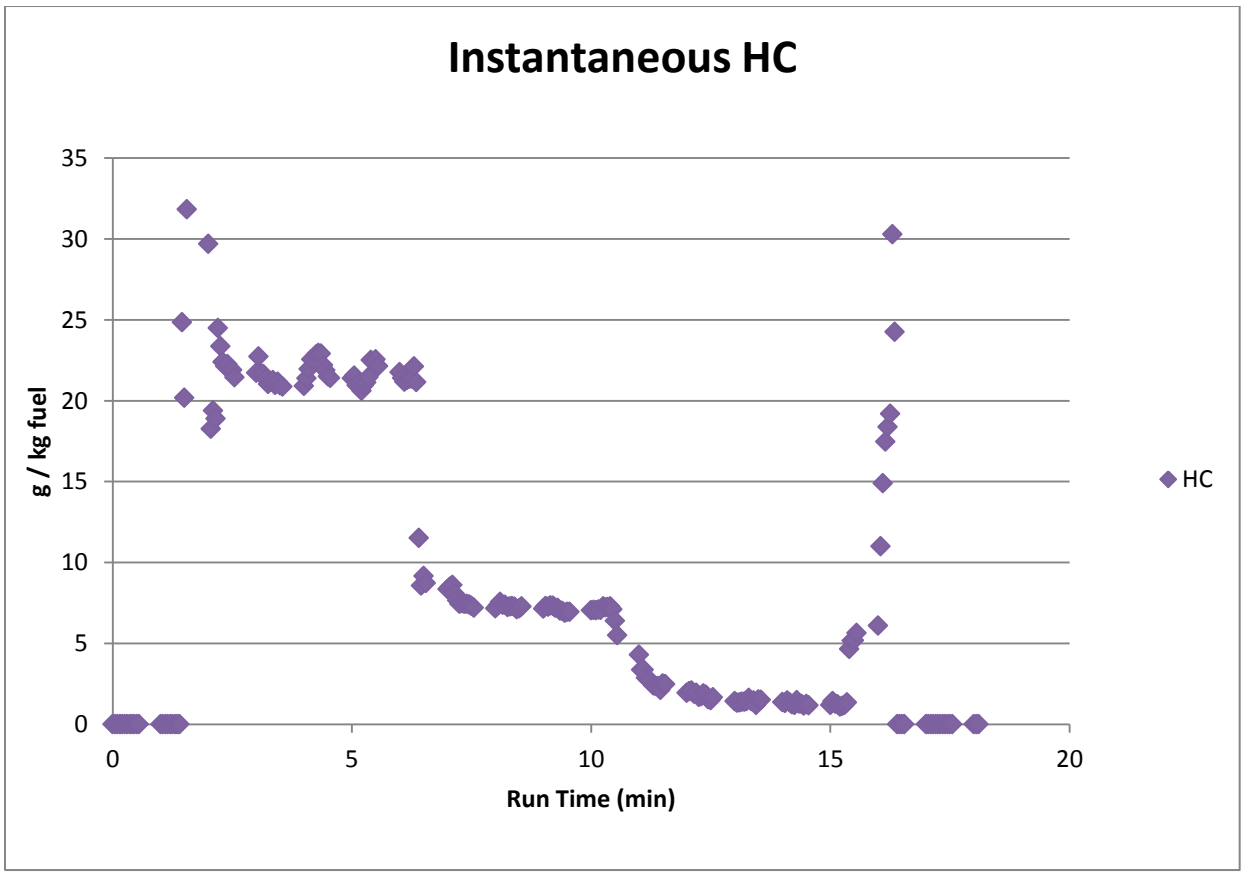


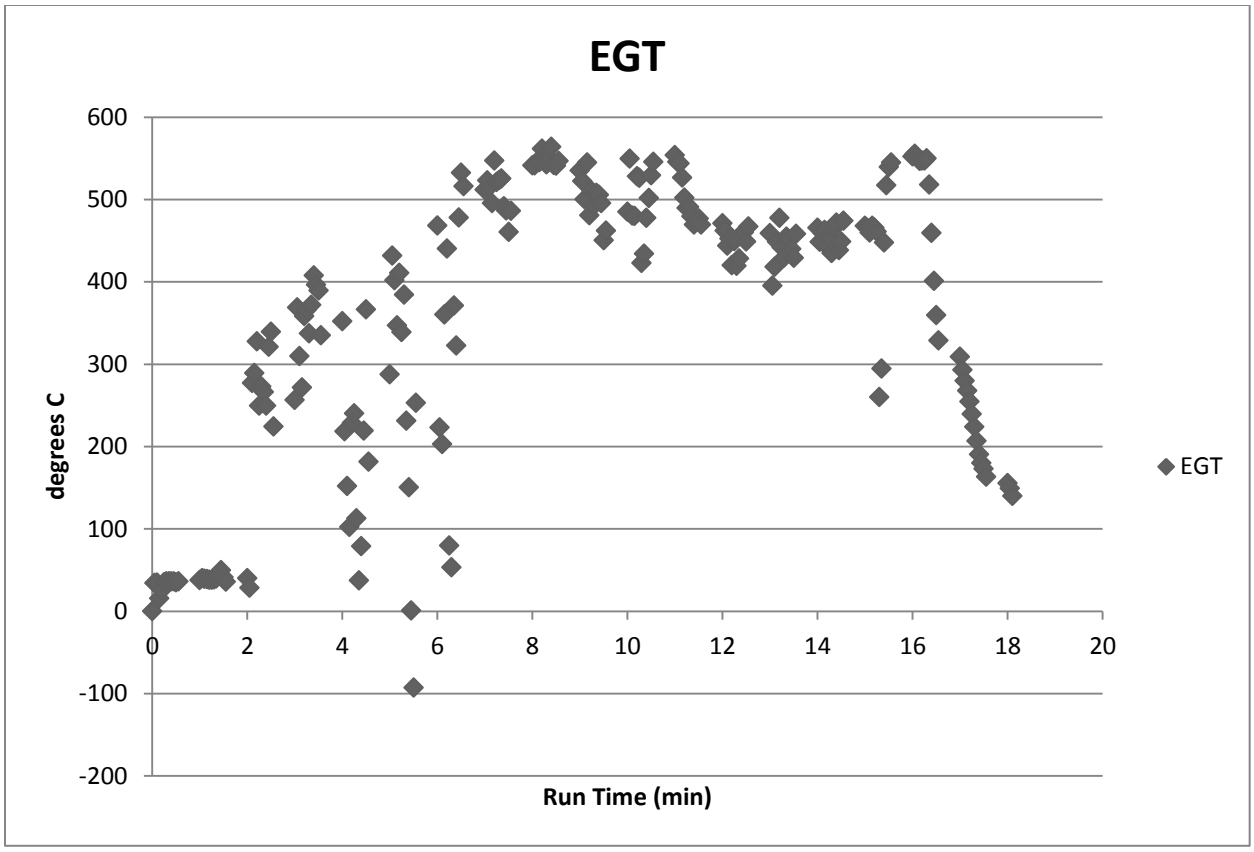


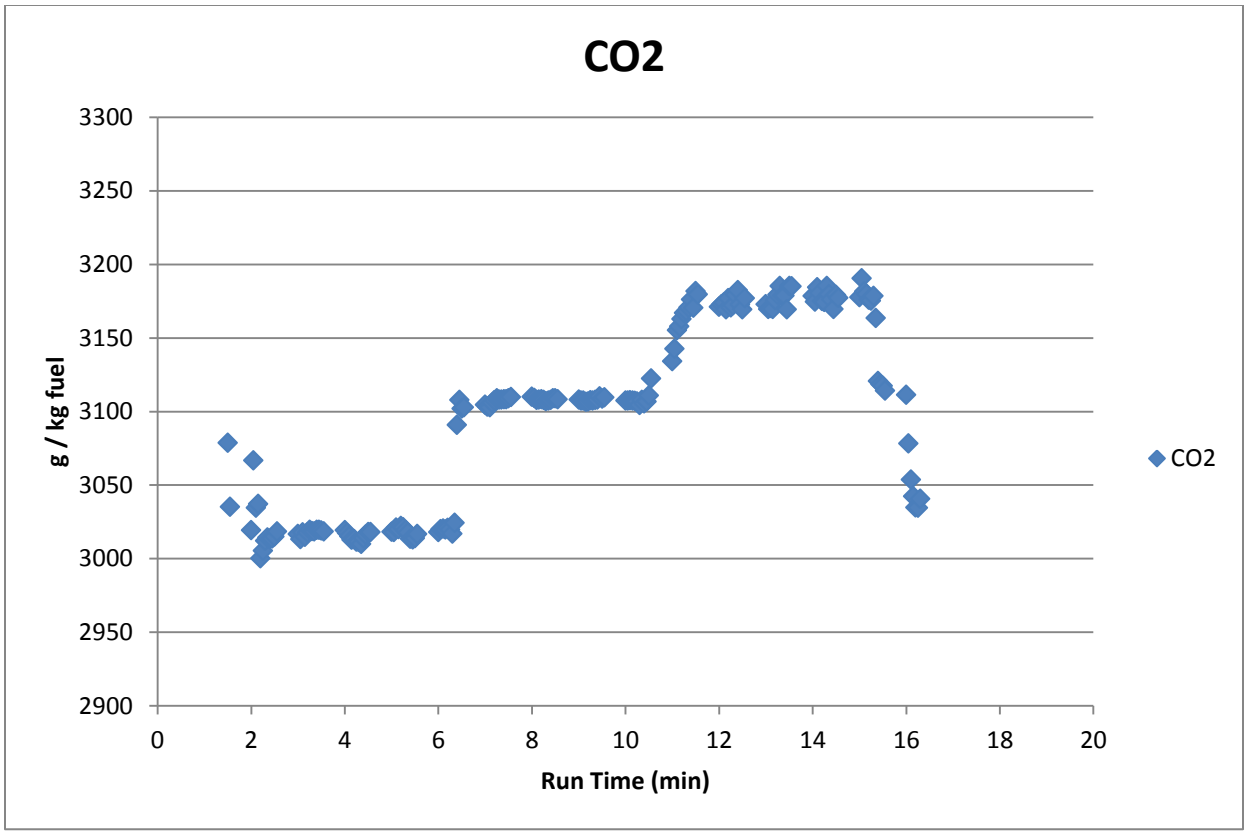

Instantaneous NO
g / kg fuel
Run Time (min)
NO
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
2
4
6
8
10
12
14
16
18
20

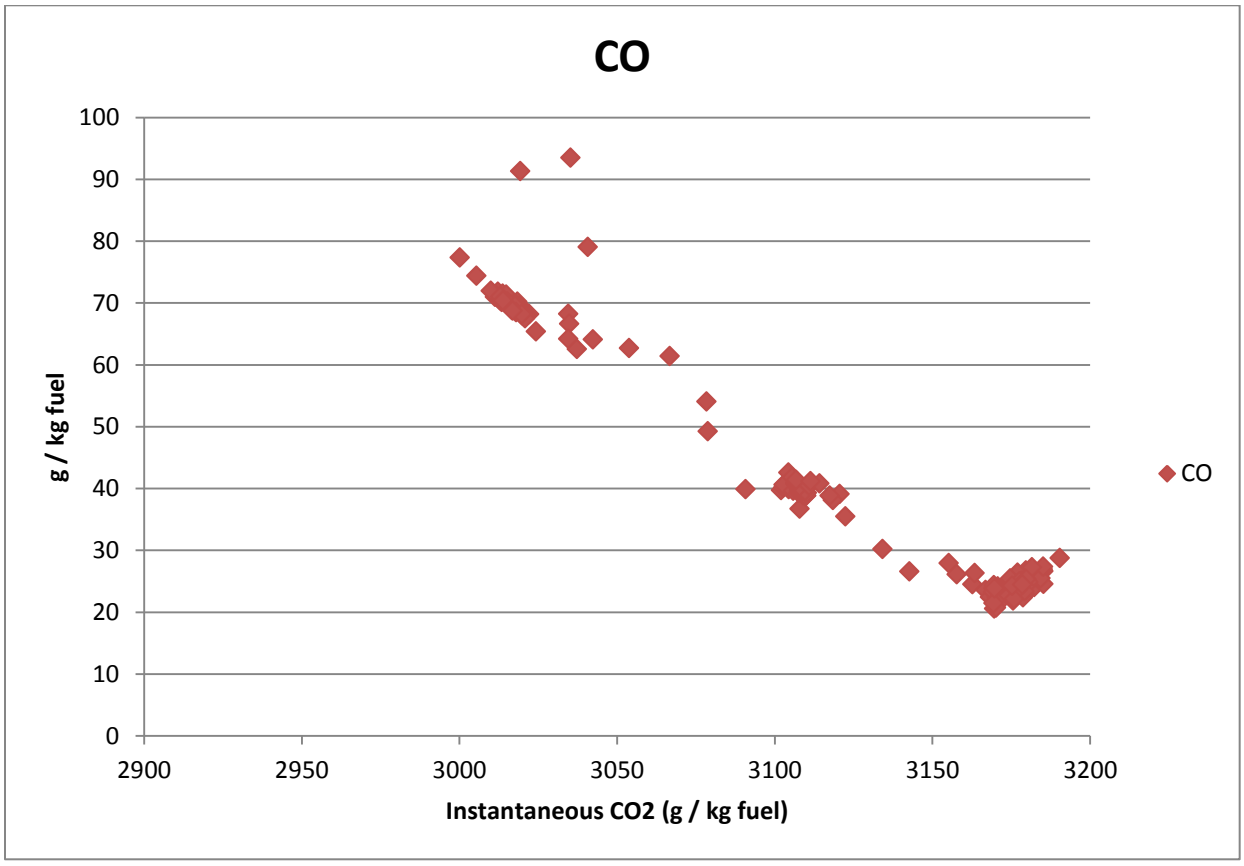

Instantaneous NO2
g / kg fuel
Run Time (min)
NO2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0
2
4
6
8
10
12
14
16
18
20

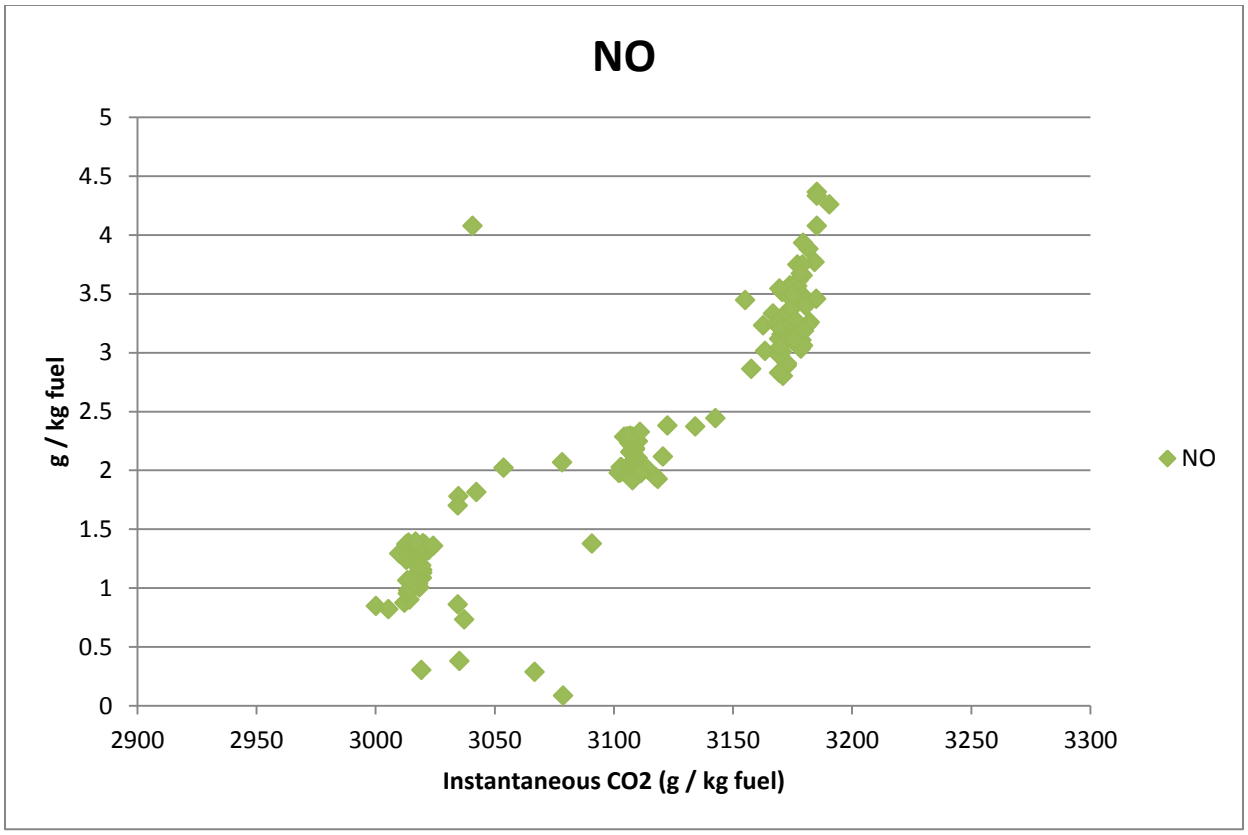

Instantaneous NOx
g / kg fuel
Run Time (min)
NOx
0
1
2
3
4
5
6
0
2
4
6
8
10
12
14
16
18
20

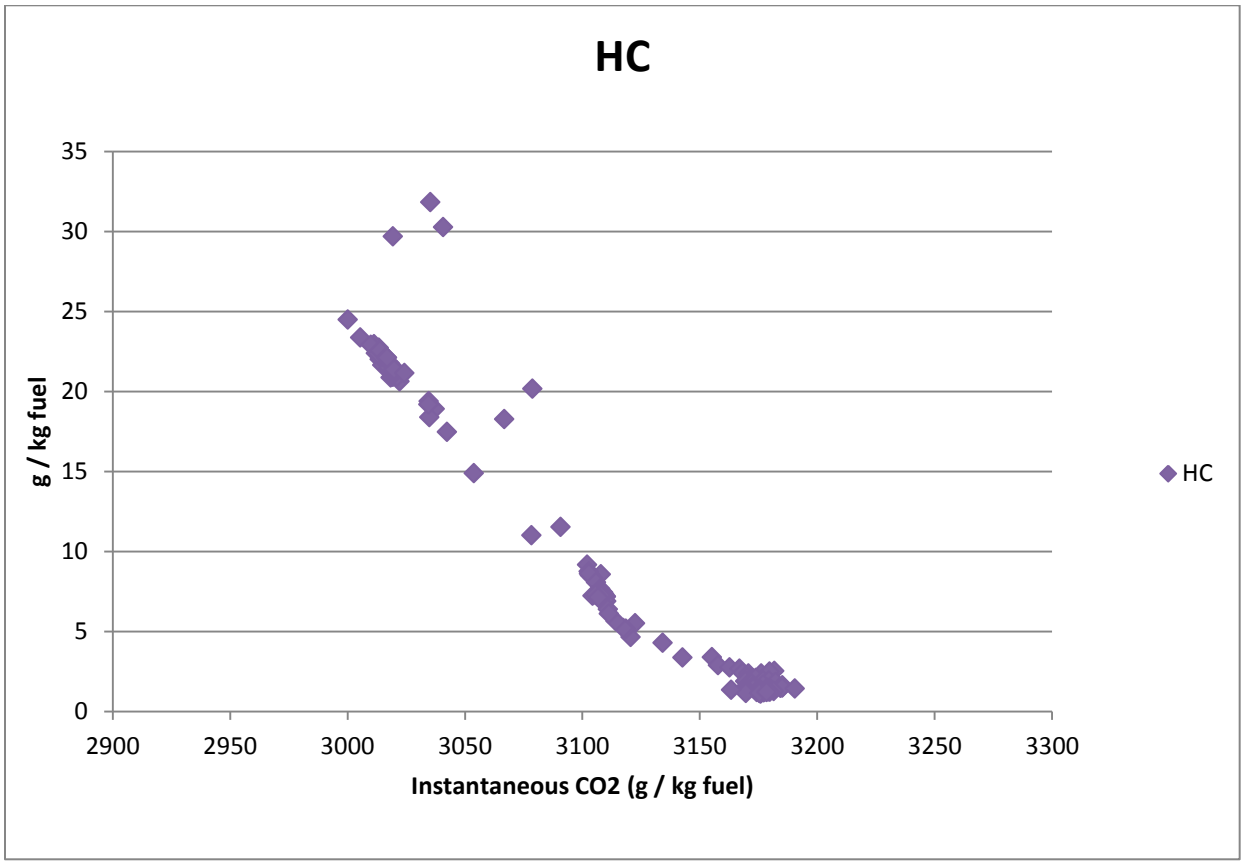

Instantaneous HC
g / kg fuel
Run Time (min)
HC
0
5
10
15
20
25
30
35
0
5
10
15
20


EGT
600
500
400
300
200
100
0
-100
-200
degrees C
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
EGT

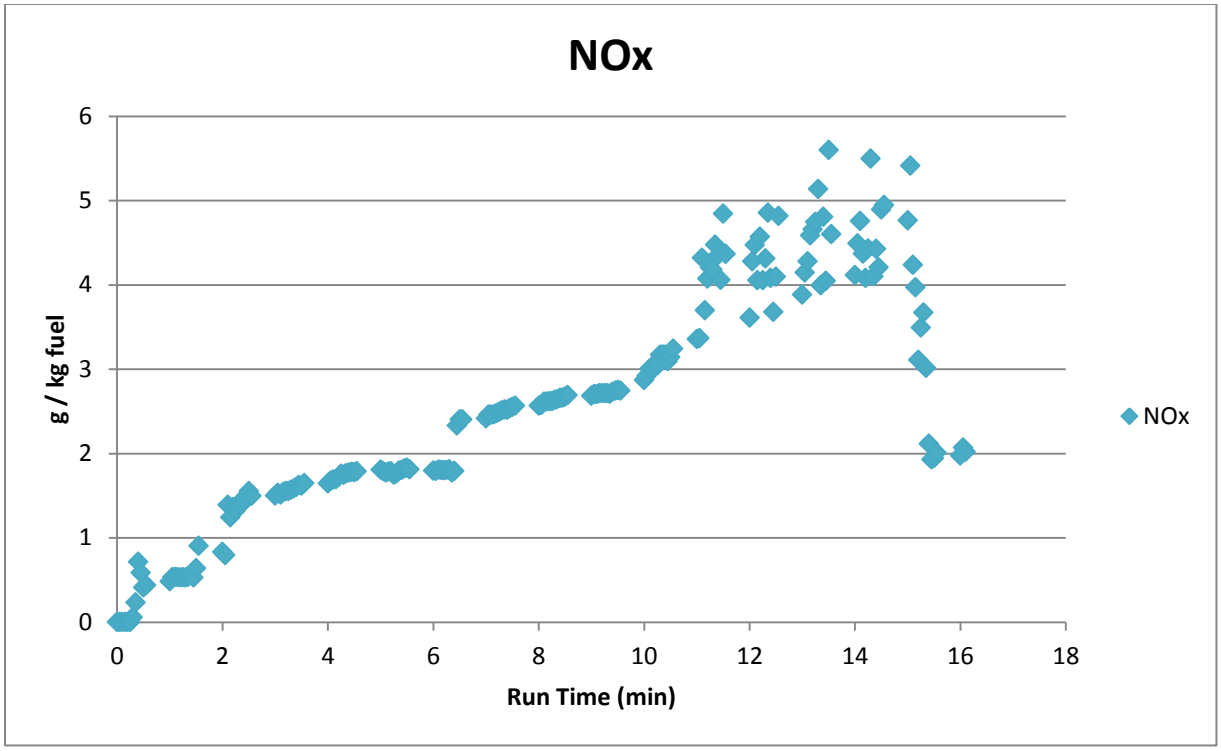

CO2
3300
3250
3200
3150
3100
3050
3000
2950
2900
g / kg fuel
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
CO2

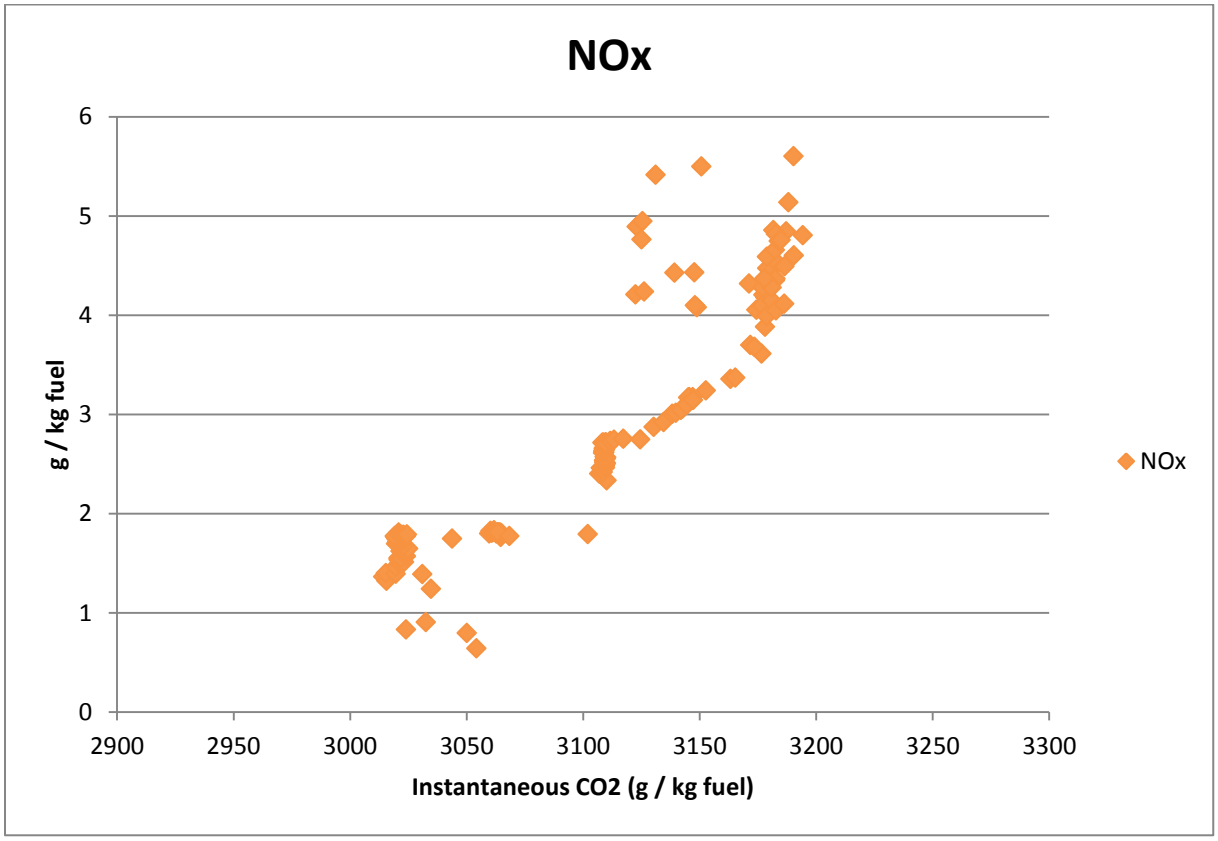

CO
100
90
80
70
60
50
40
30
20
10
0
g / kg fuel
2900
2950
3000
3050
3100
3150
3200
Instantaneous CO2 (g / kg fuel)
CO


NO
g / kg fuel
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
2900
2950
3000
3050
3100
3150
3200
3250
3300
Instantaneous CO2 (g / kg fuel)
NO

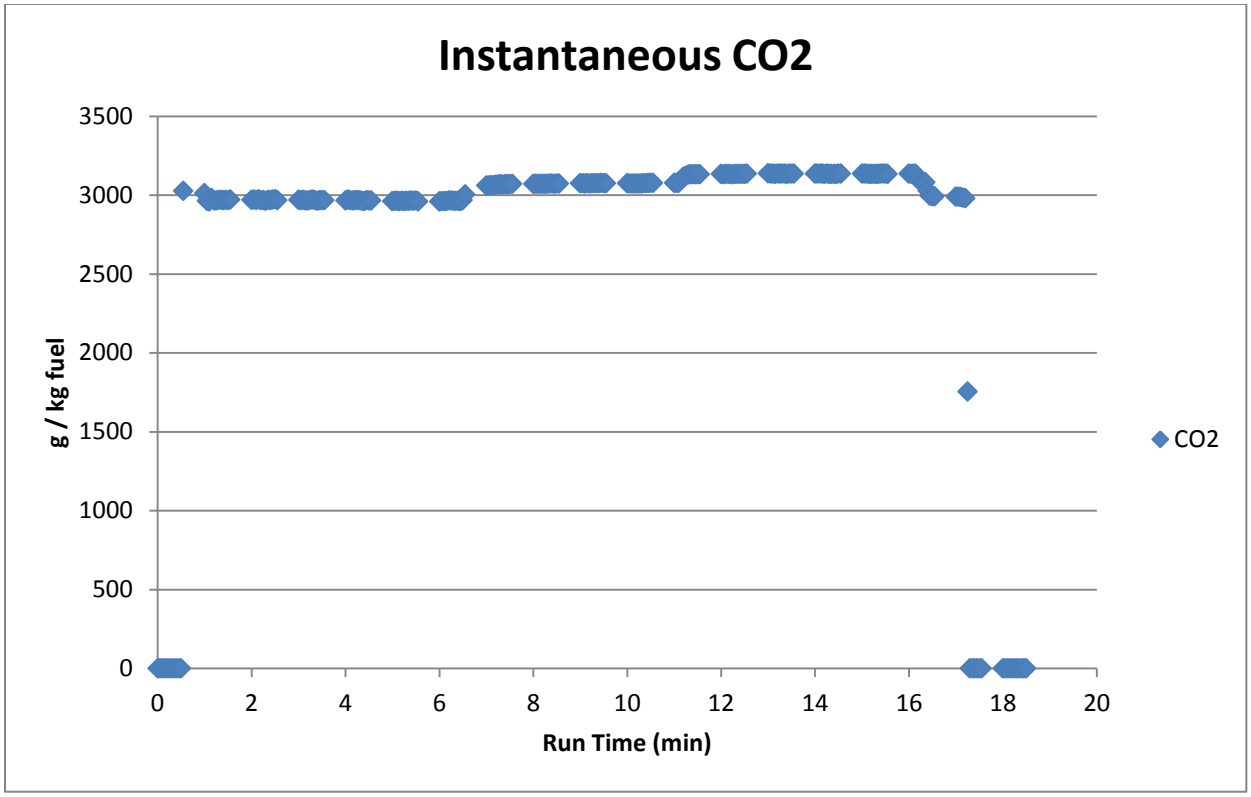

HC
g / kg fuel
35
30
25
20
15
10
5
0
2900
2950
3000
3050
3100
3150
3200
3250
3300
Instantaneous CO2 (g / kg fuel)
HC

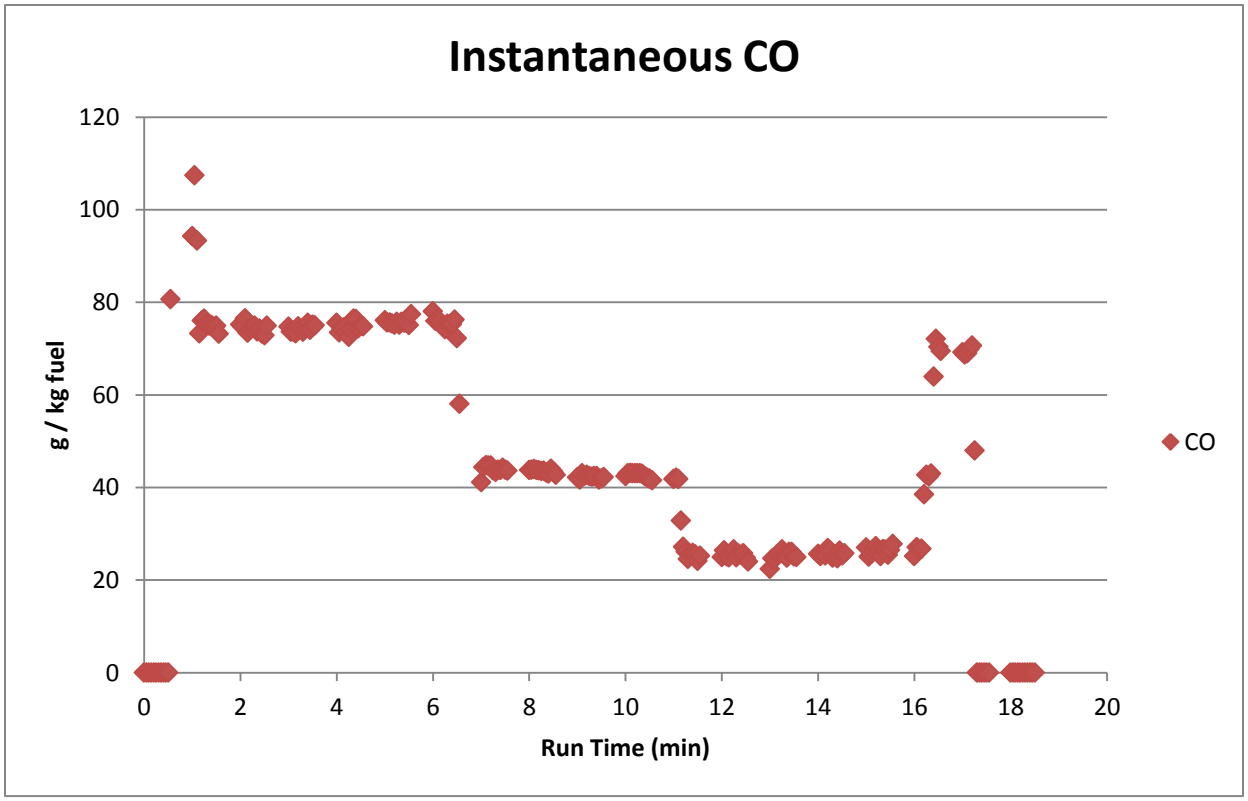
Salina4 Jet A Combined NOx 10/24/2012 PT6

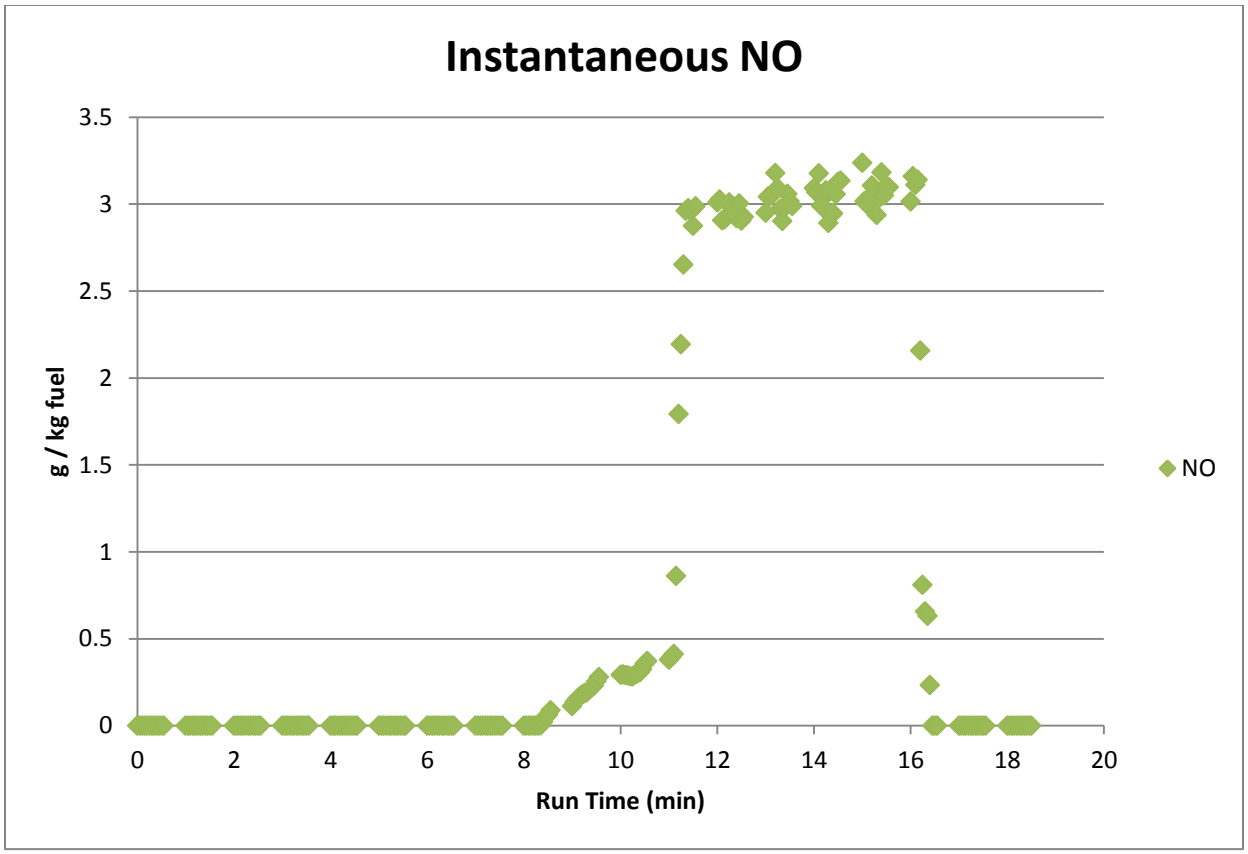


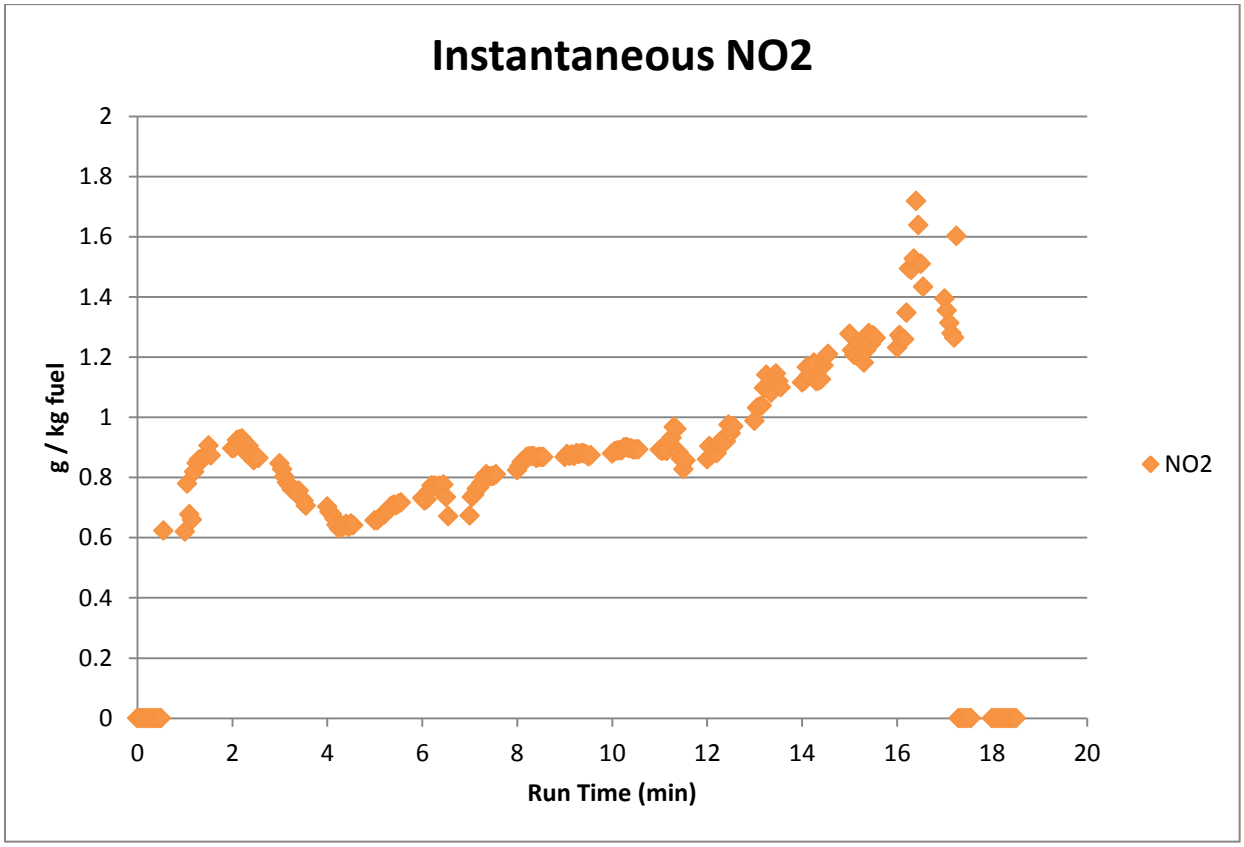


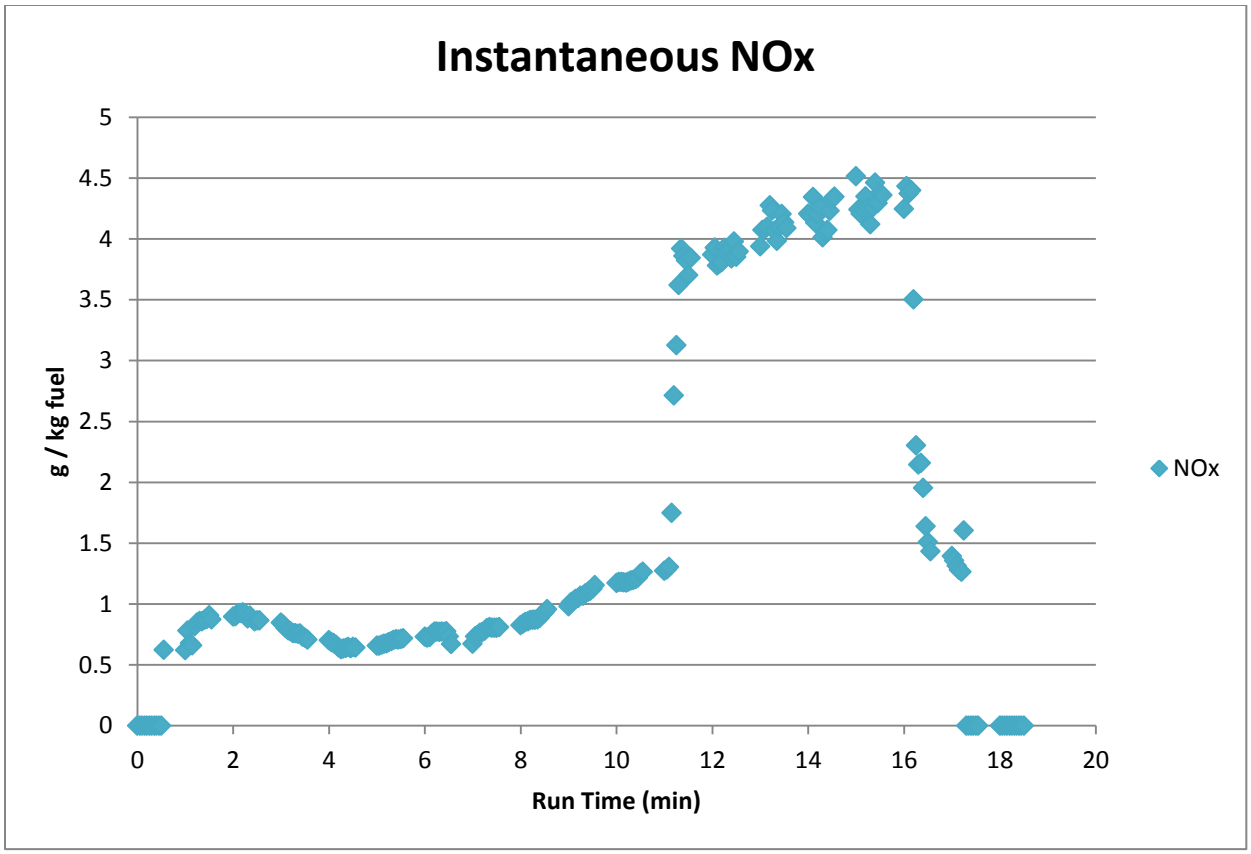
Salina4 HRJ NCF 10/24/2012 PT6

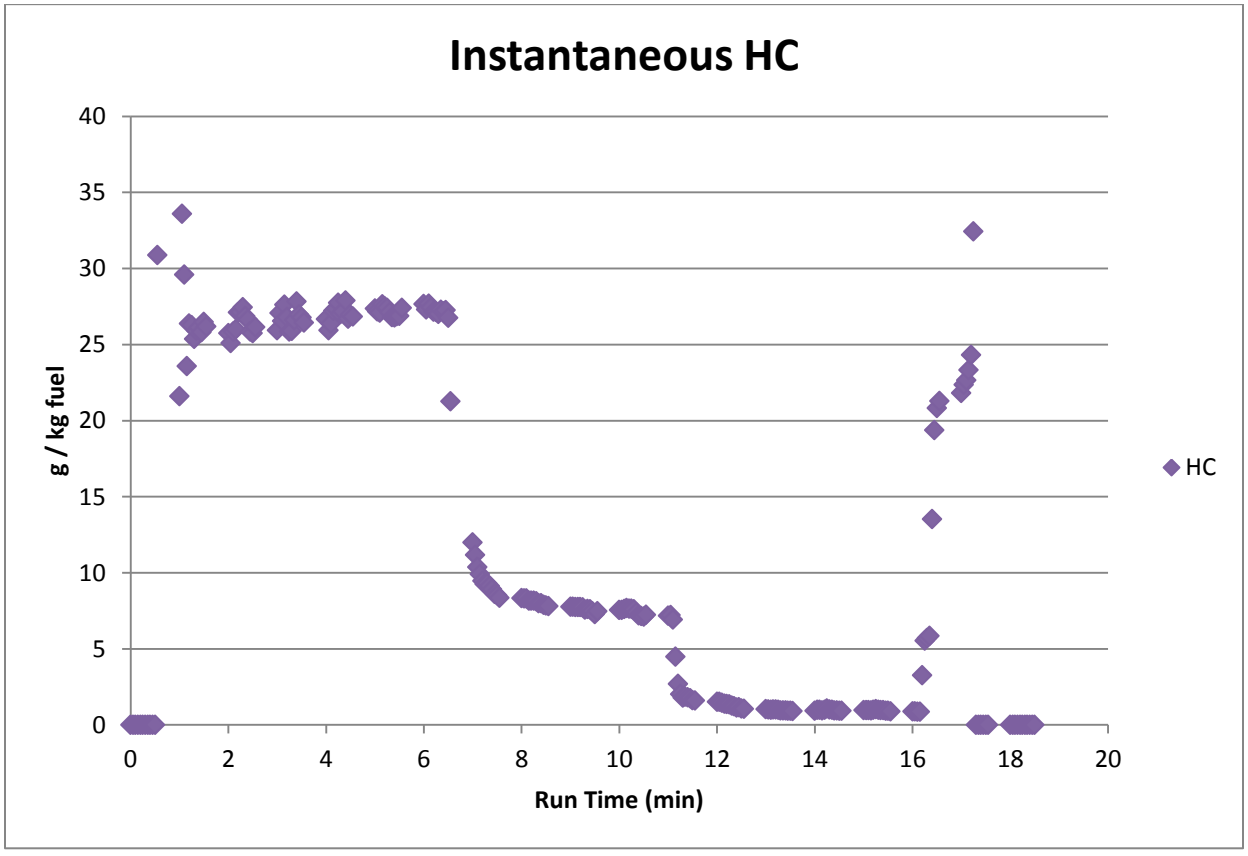


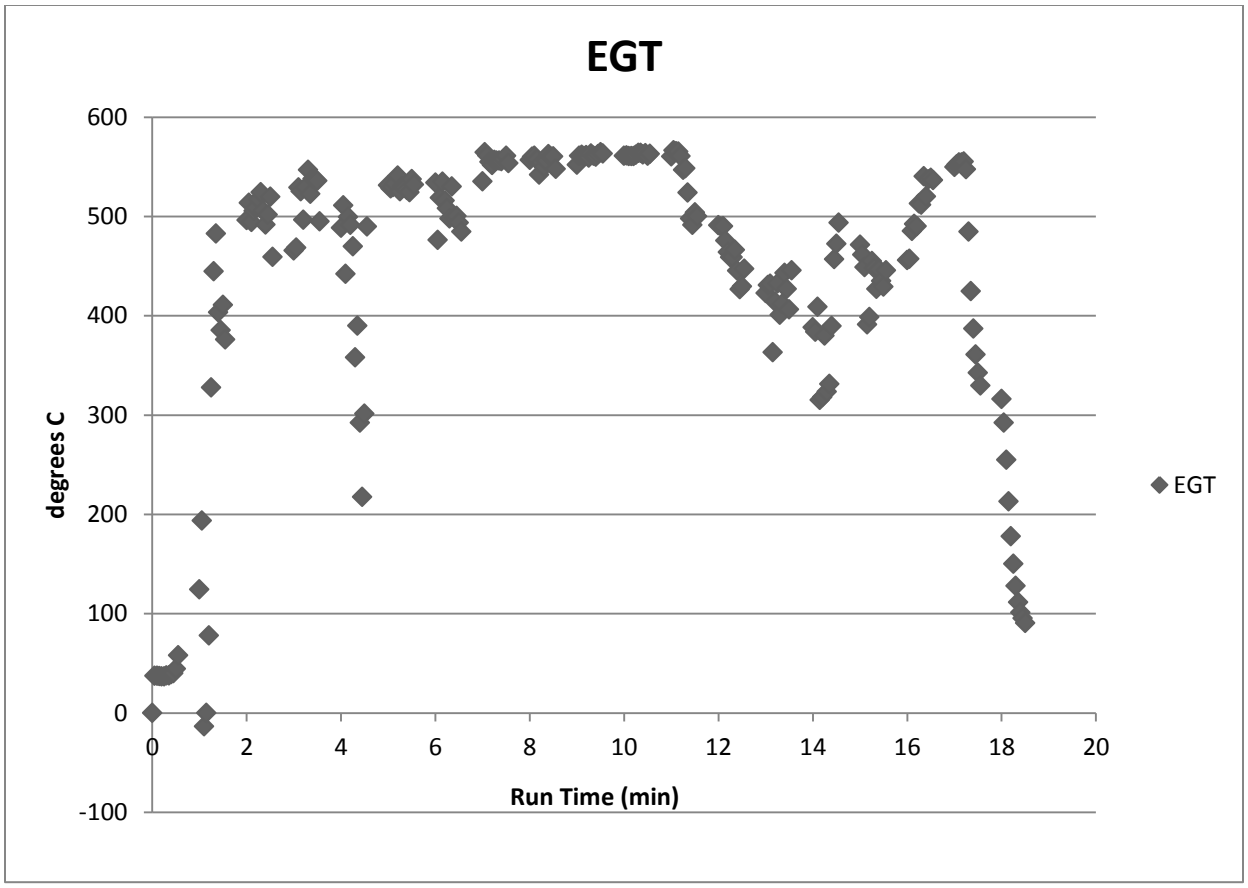


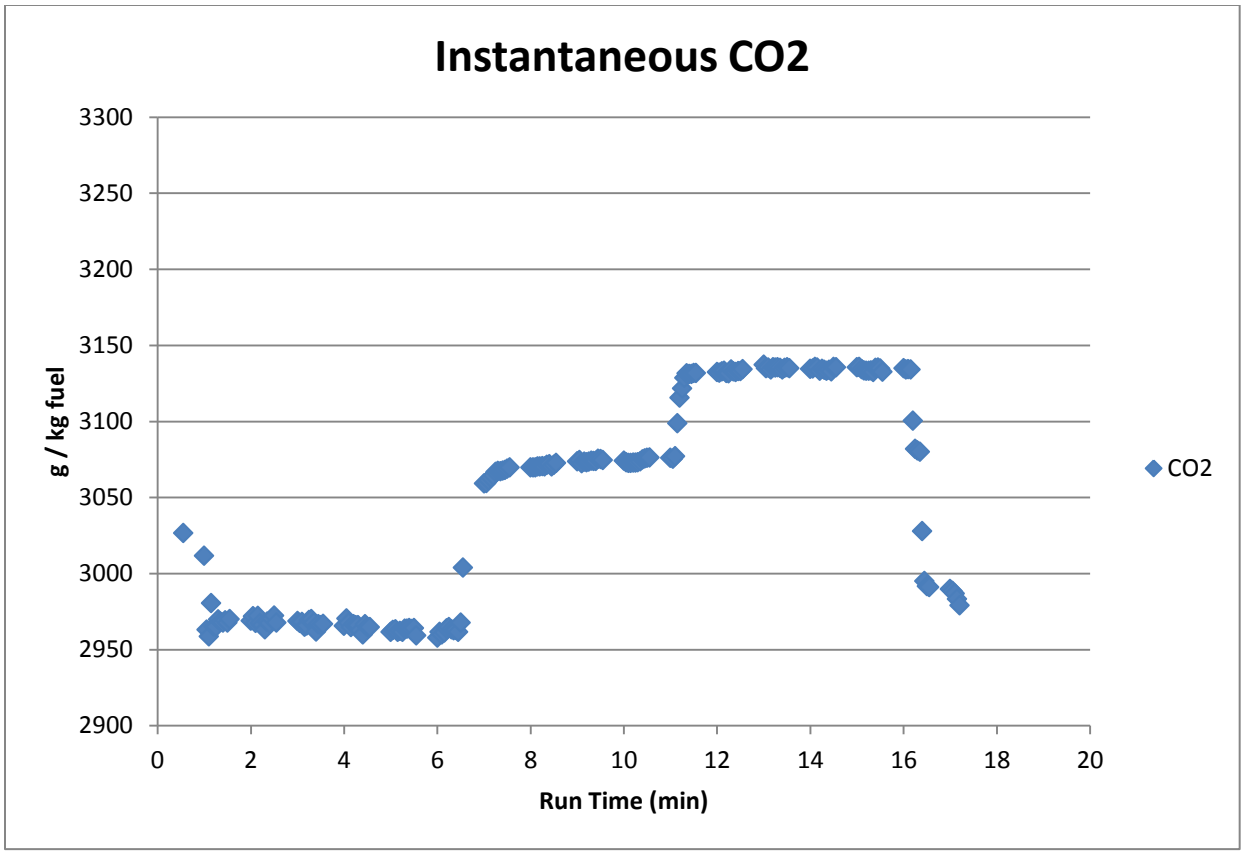

Instantaneous NO
g / kg fuel
Run Time (min)
NO
0
0.5
1
1.5
2
2.5
3
3.5
0
2
4
6
8
10
12
14
16
18
20

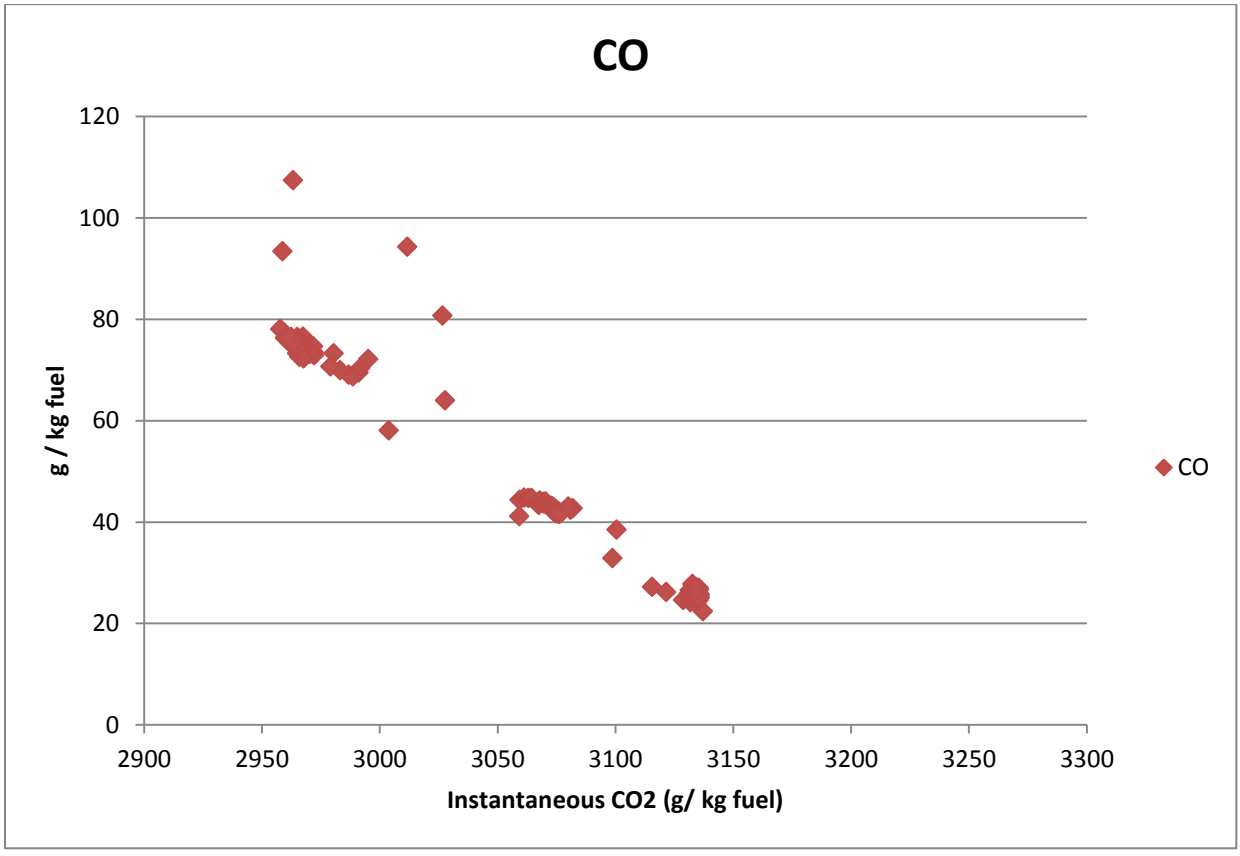

Instantaneous NO2
g / kg fuel
Run Time (min)
NO2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
2
4
6
8
10
12
14
16
18
20

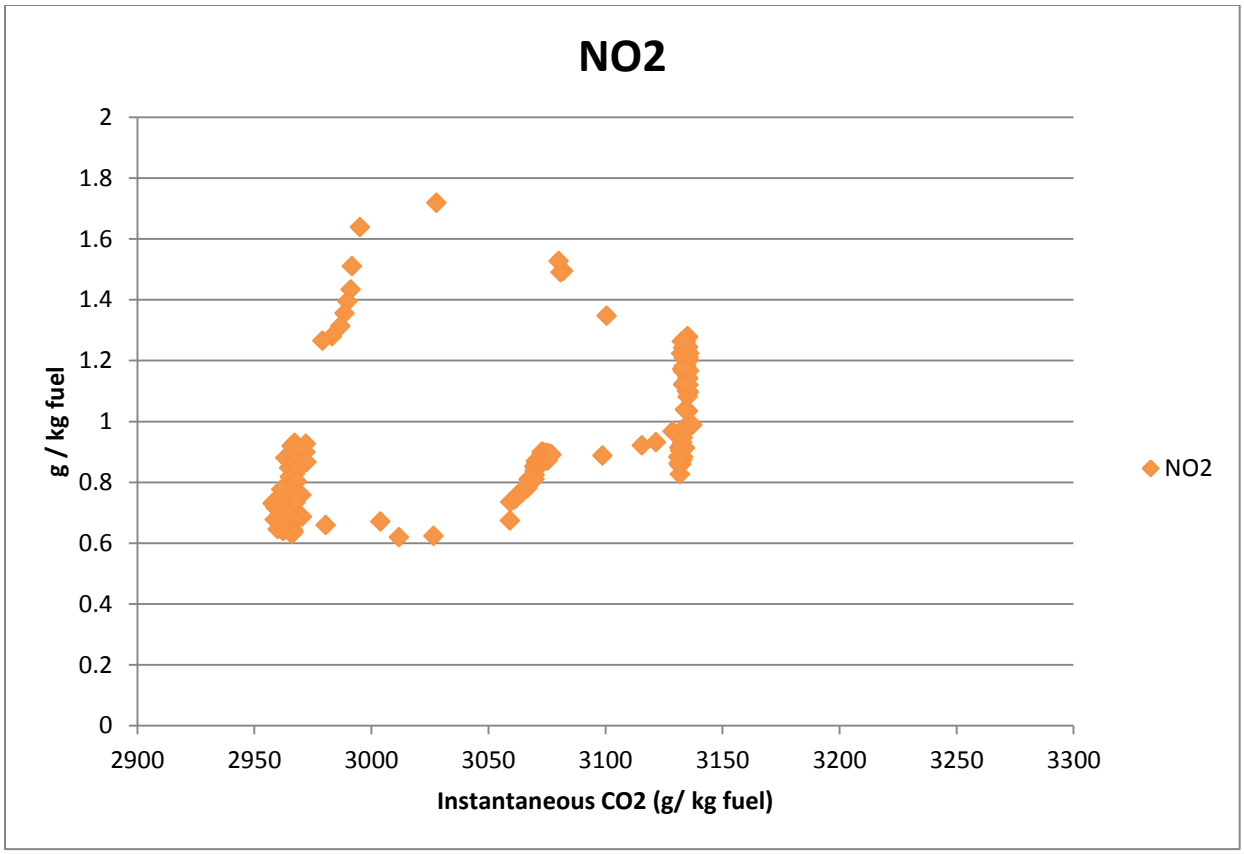

Instantaneous NOx
g / kg fuel
Run Time (min)
NOx
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
2
4
6
8
10
12
14
16
18
20

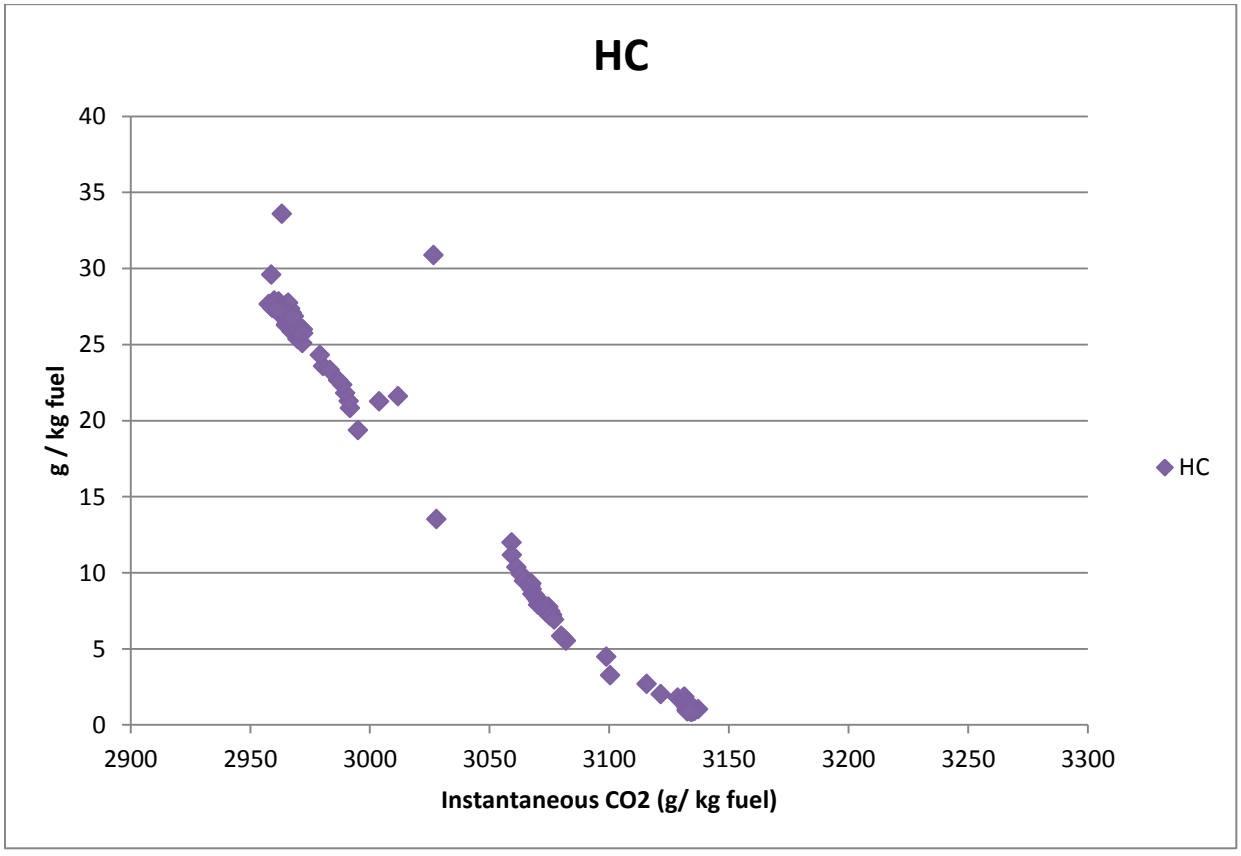

Instantaneous HC
g / kg fuel
Run Time (min)
HC
0
5
10
15
20
25
30
35
40
0
2
4
6
8
10
12
14
16
18
20


EGT
600
500
400
300
200
100
0
-100
degrees C
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
EGT

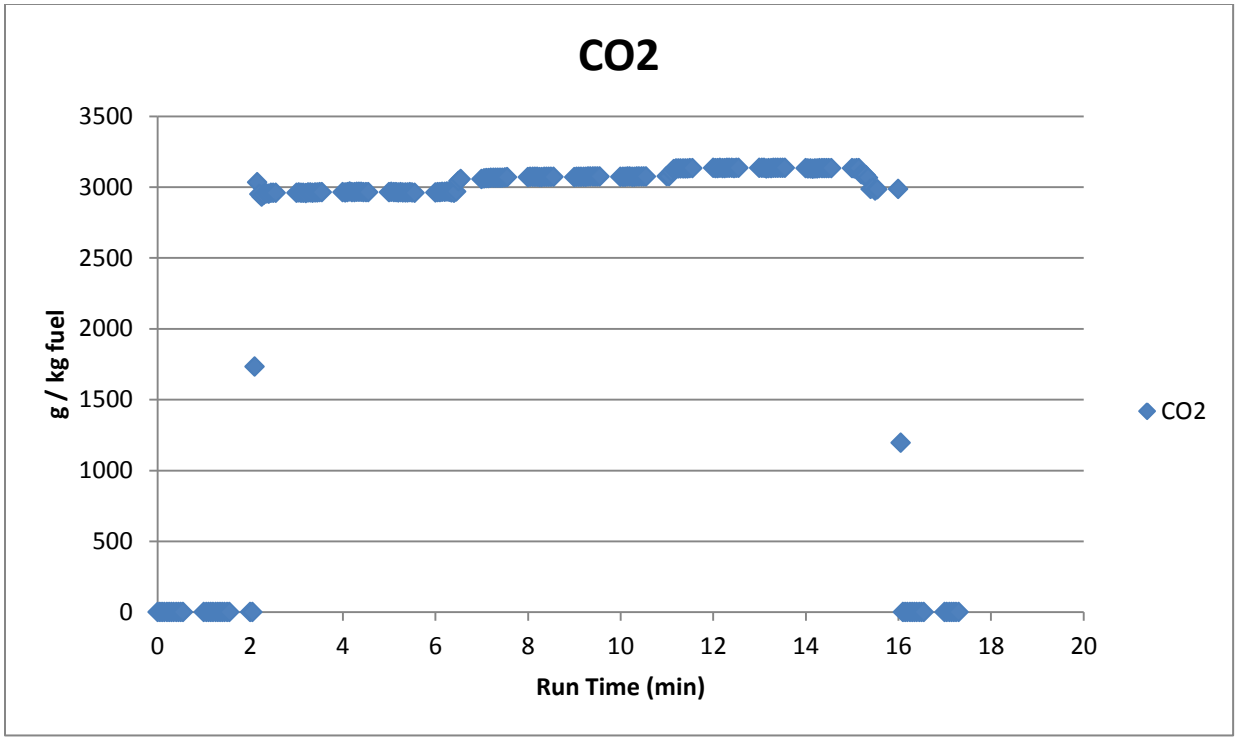

Instantaneous CO2
3300
3250
3200
3150
3100
3050
3000
2950
2900
g / kg fuel
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
CO2

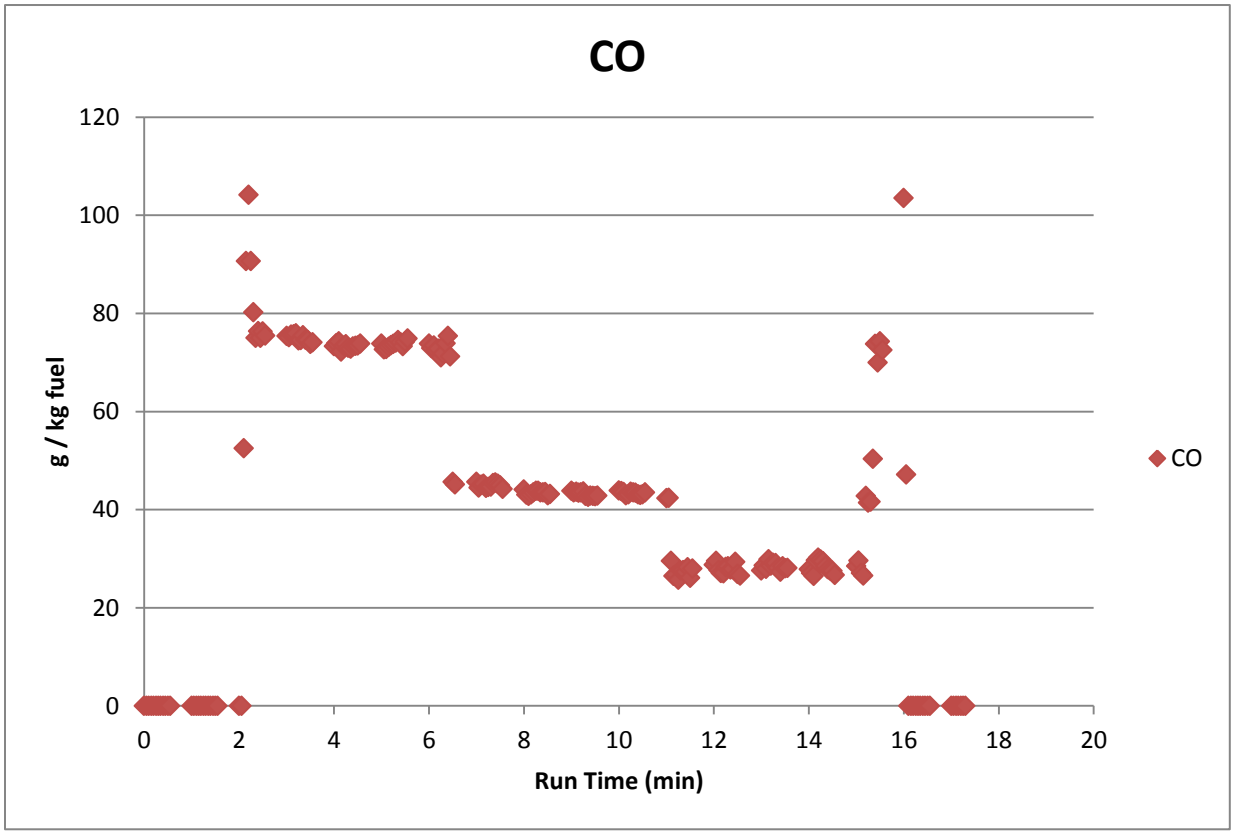

CO
120
100
80
60
40
20
0
g / kg fuel
2900
2950
3000
3050
3100
3150
3200
3250
3300
Instantaneous CO2 (g/ kg fuel)
CO

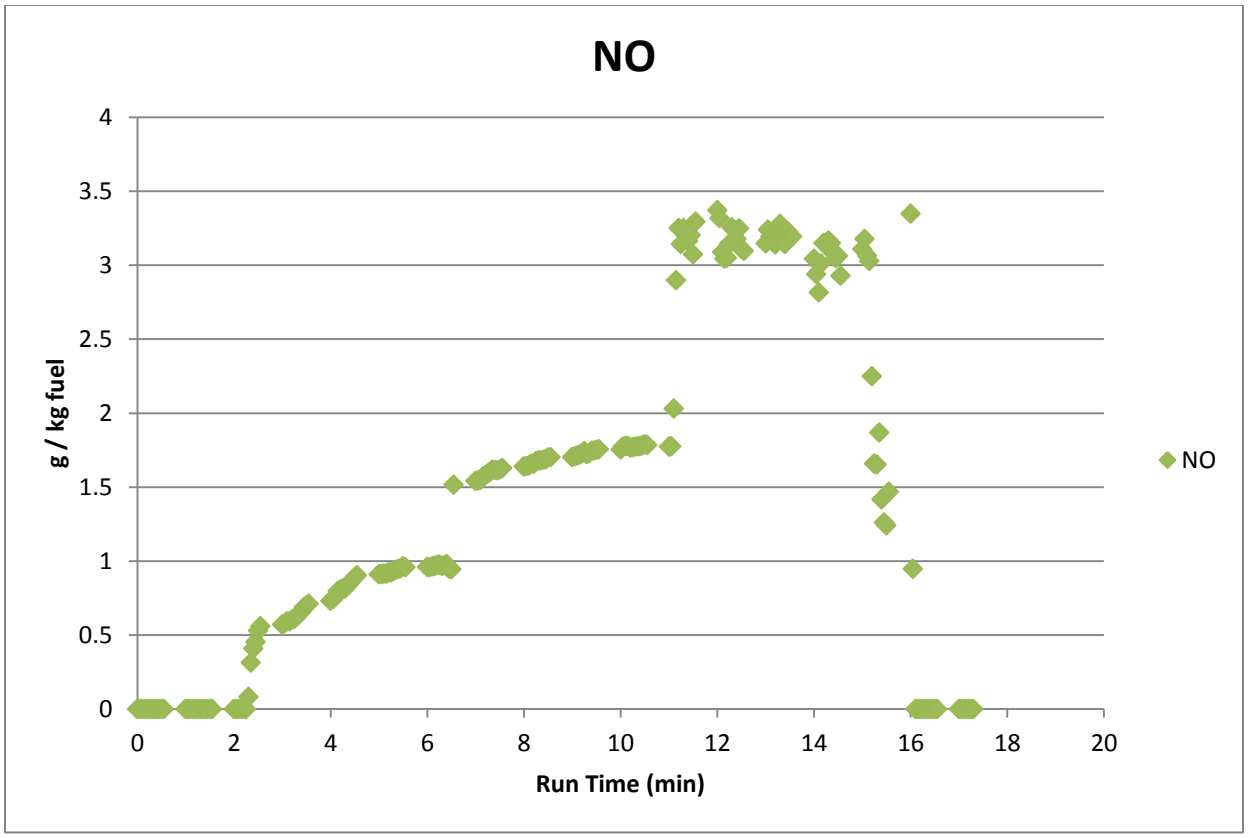

NO2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
g / kg fuel
2900
2950
3000
3050
3100
3150
3200
3250
3300
Instantaneous CO2 (g/ kg fuel)
NO2

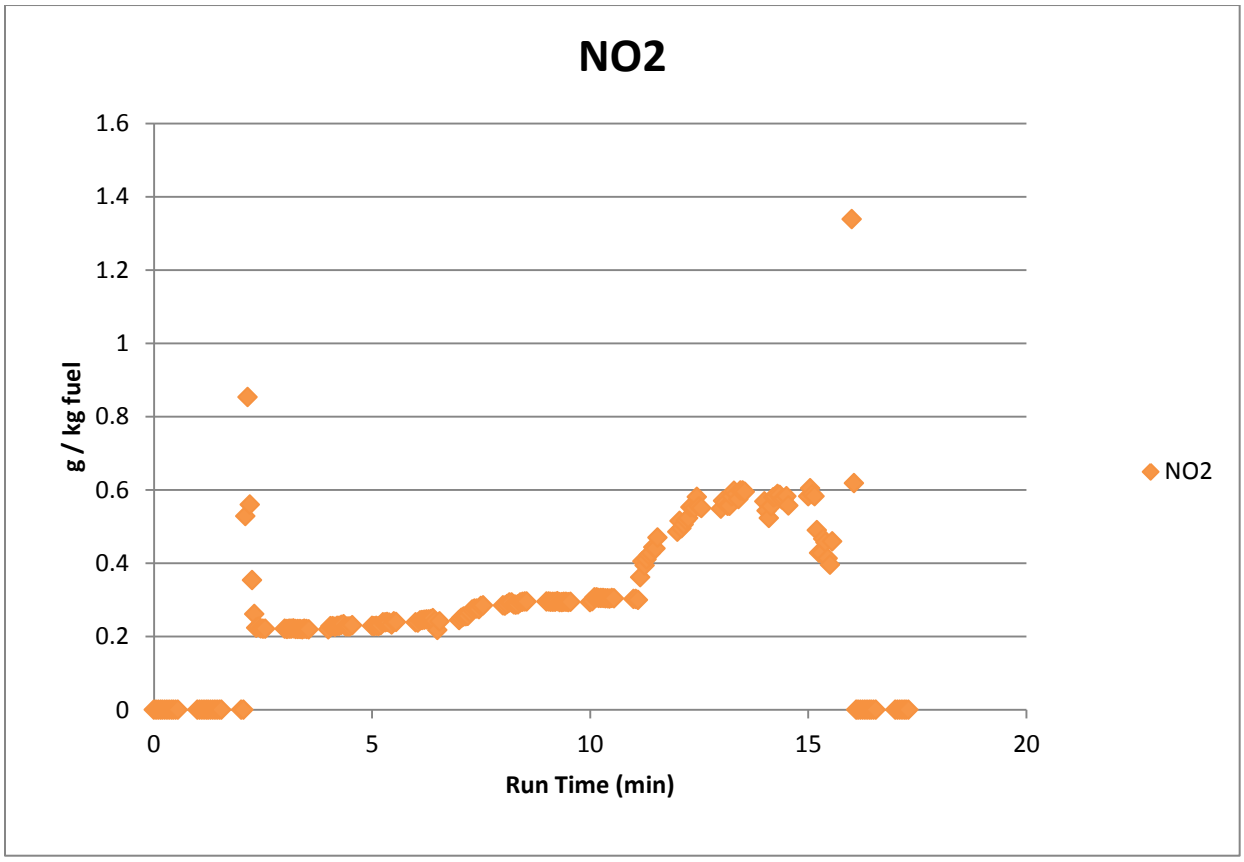

HC
40
35
30
25
20
15
10
5
0
g / kg fuel
2900
2950
3000
3050
3100
3150
3200
3250
3300
Instantaneous CO2 (g/ kg fuel)
HC

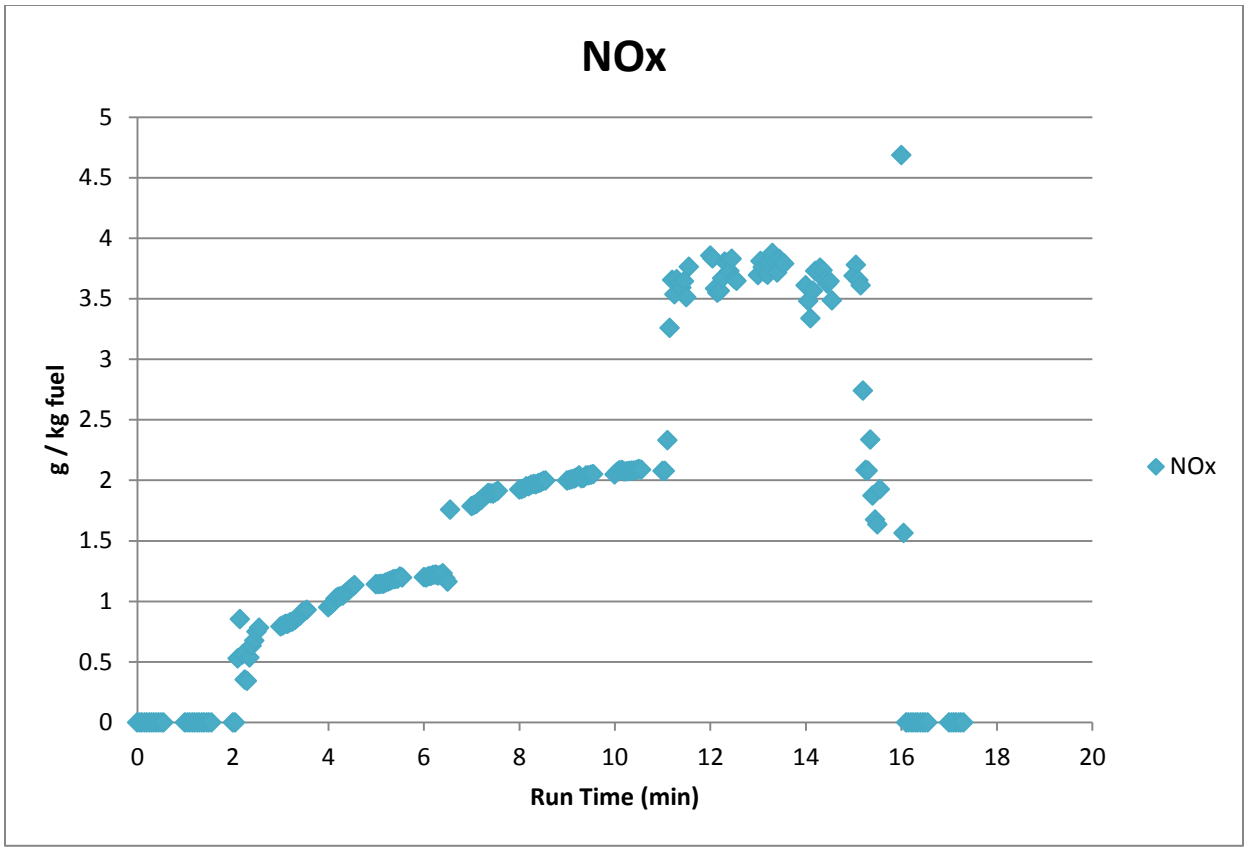
Salina4 HRJ CF 10/24/2012 PT6

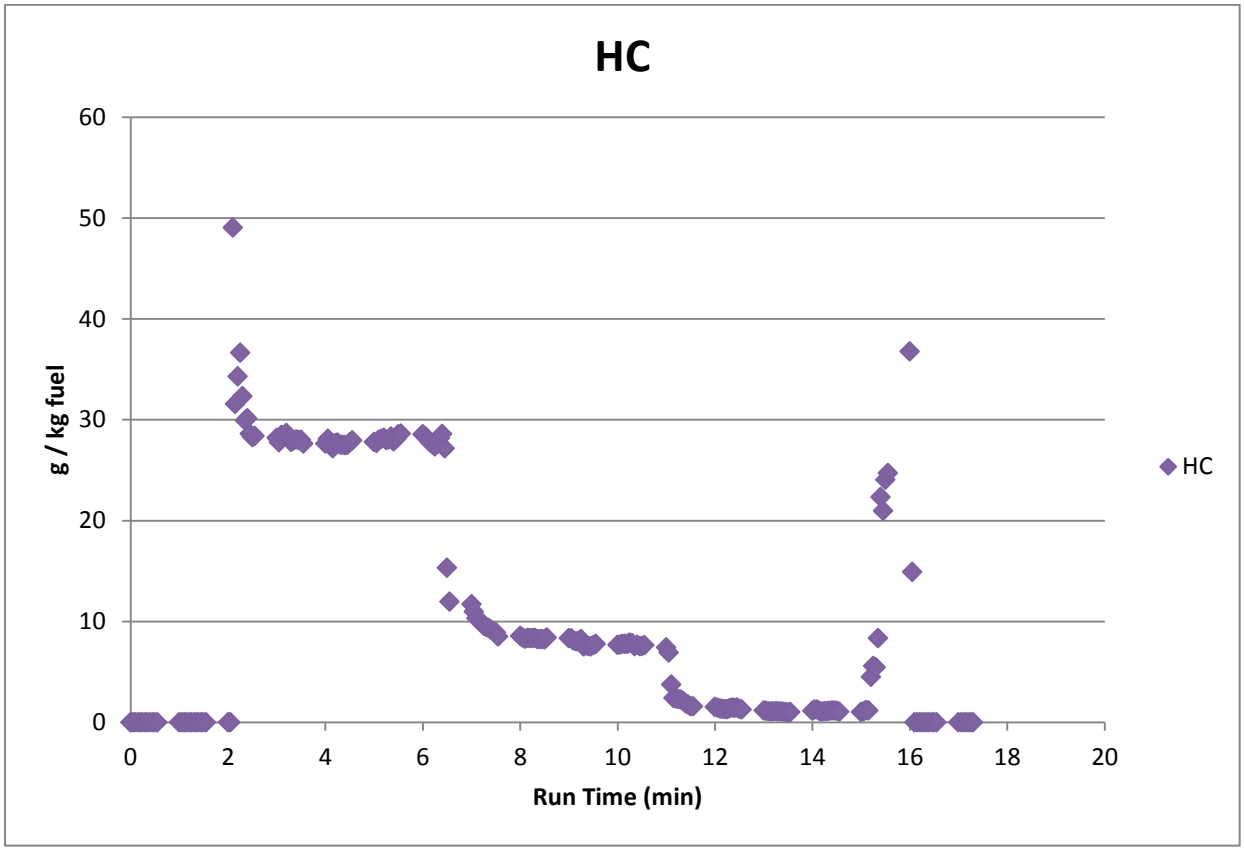


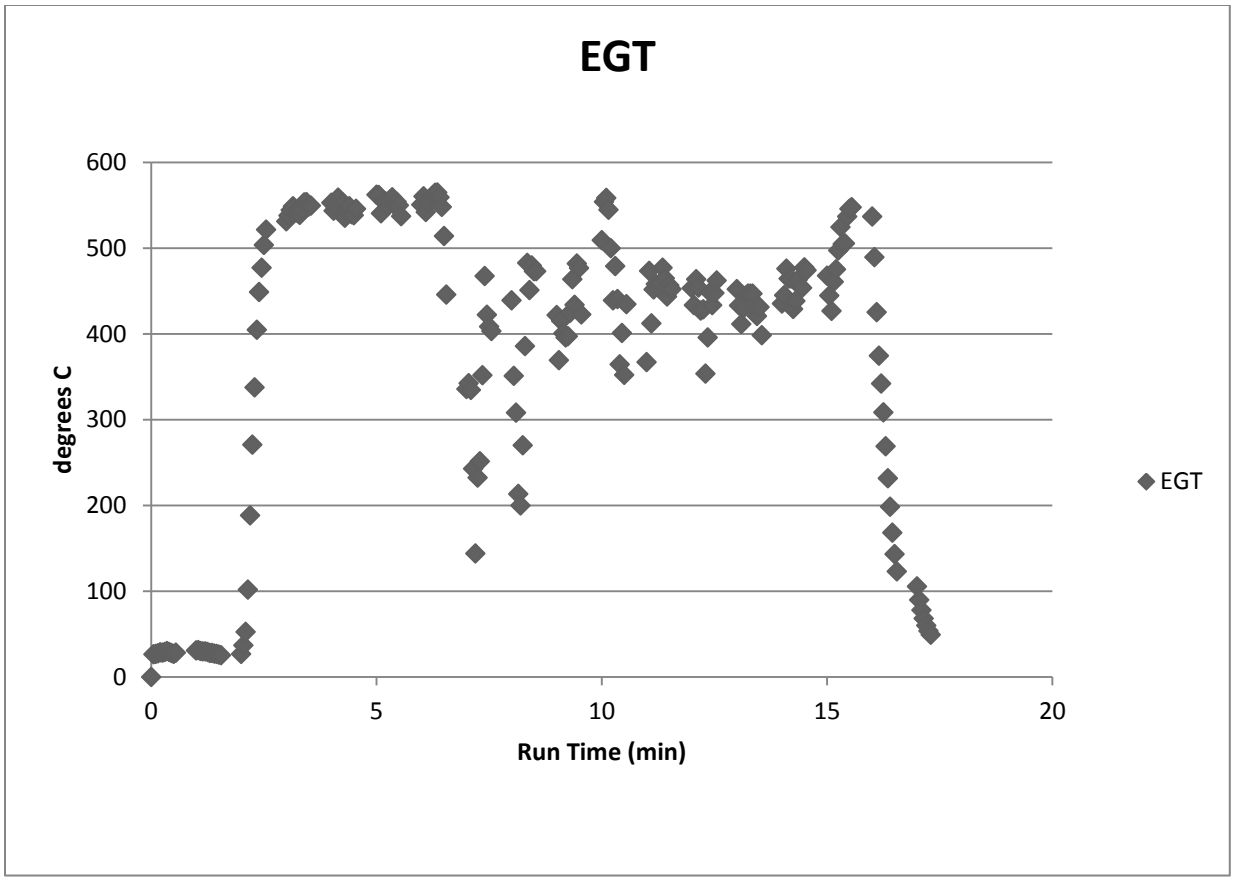


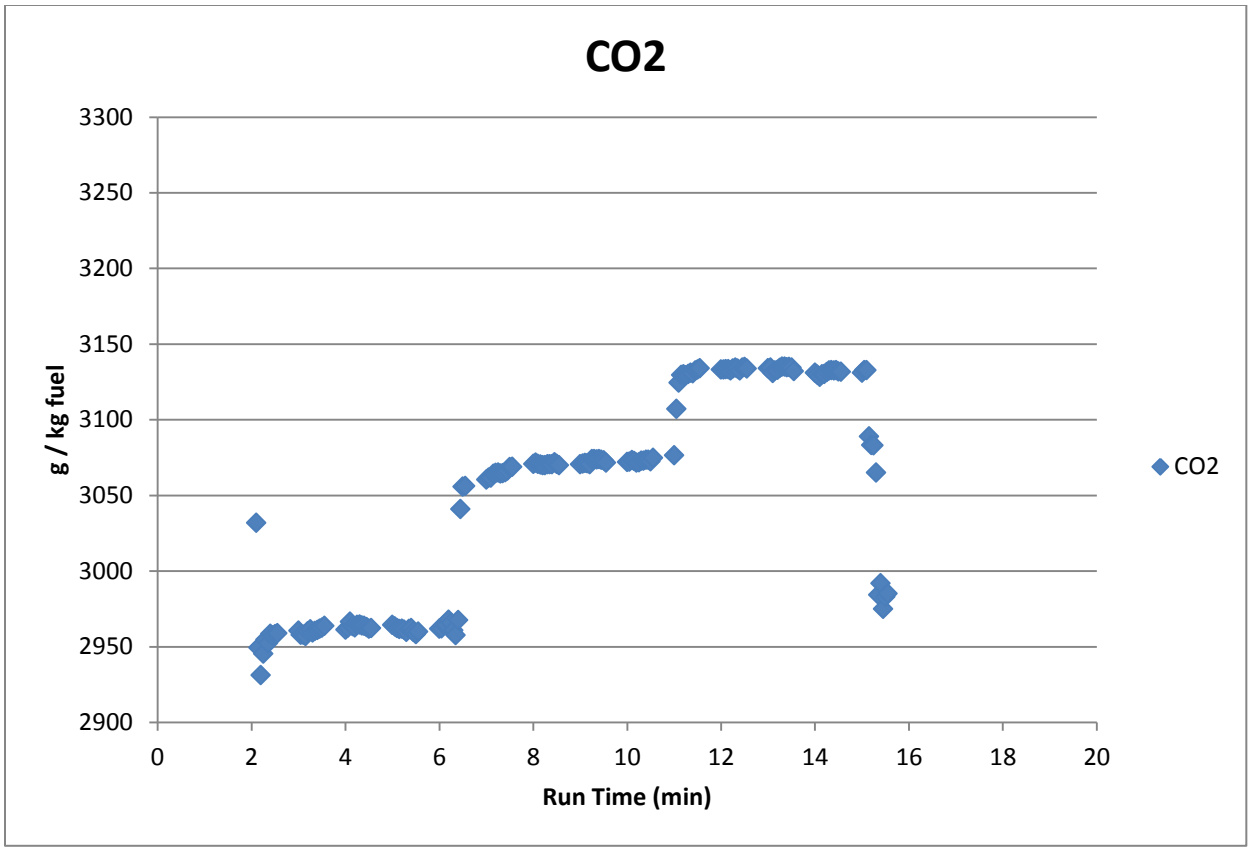

NO
g / kg fuel
Run Time (min)
NO
0
0.5
1
1.5
2
2.5
3
3.5
4
0
2
4
6
8
10
12
14
16
18
20

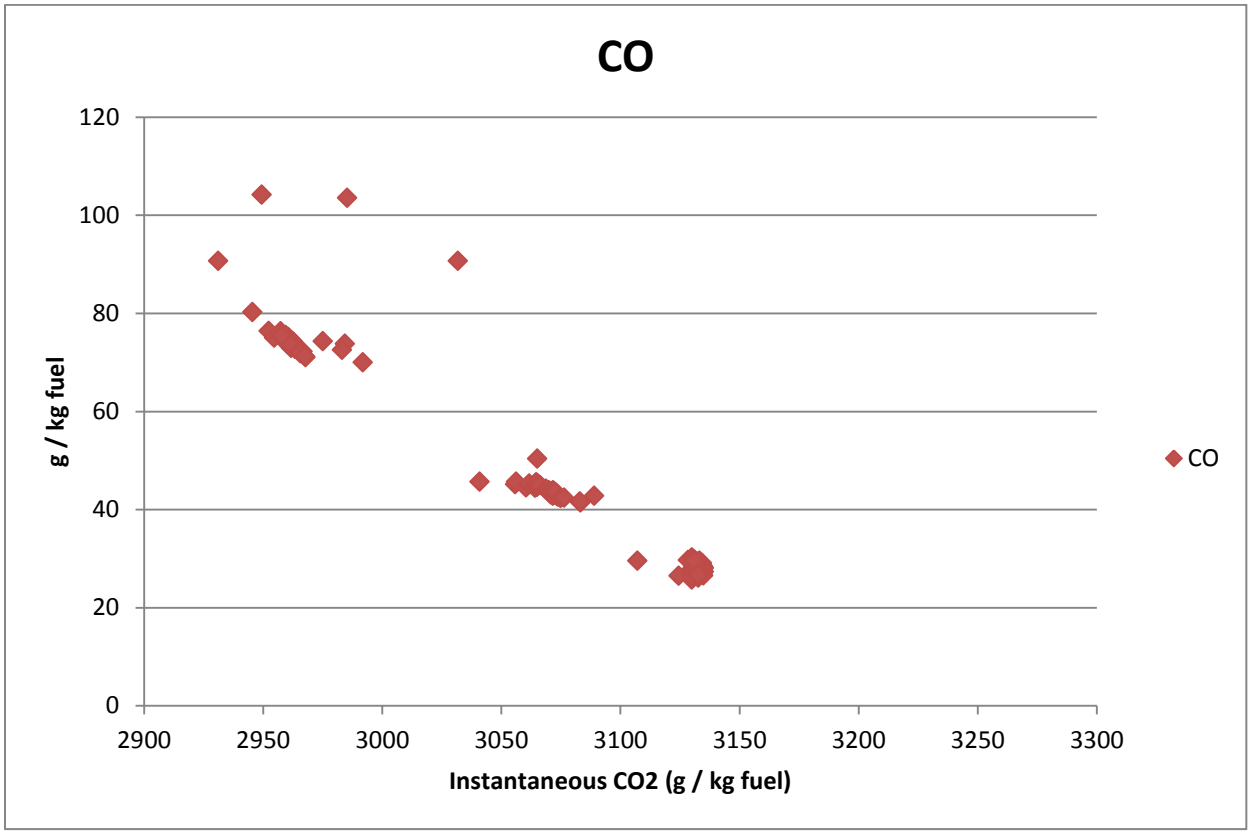

NO2
g / kg fuel
Run Time (min)
NO2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
0
5
10
15
20

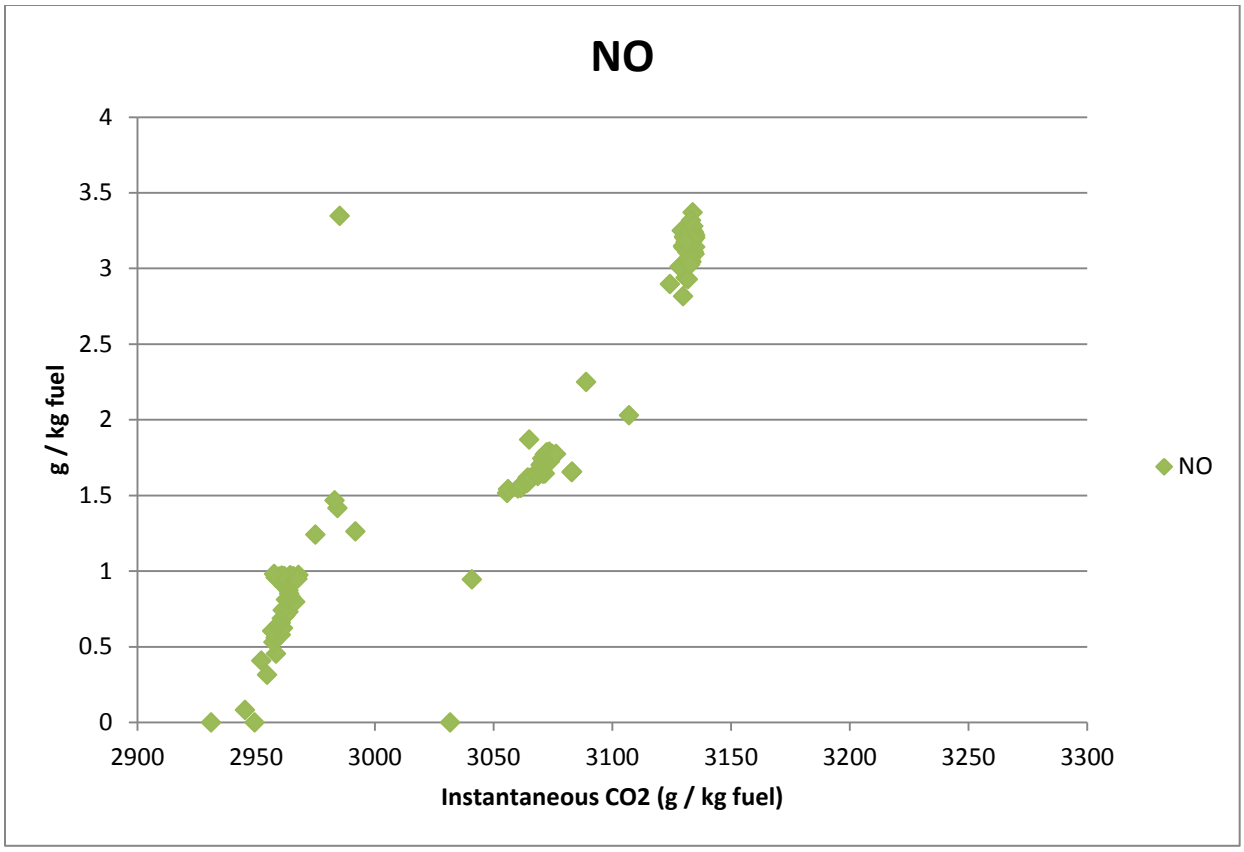

NOx
g / kg fuel
Run Time (min)
NOx
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
2
4
6
8
10
12
14
16
18
20

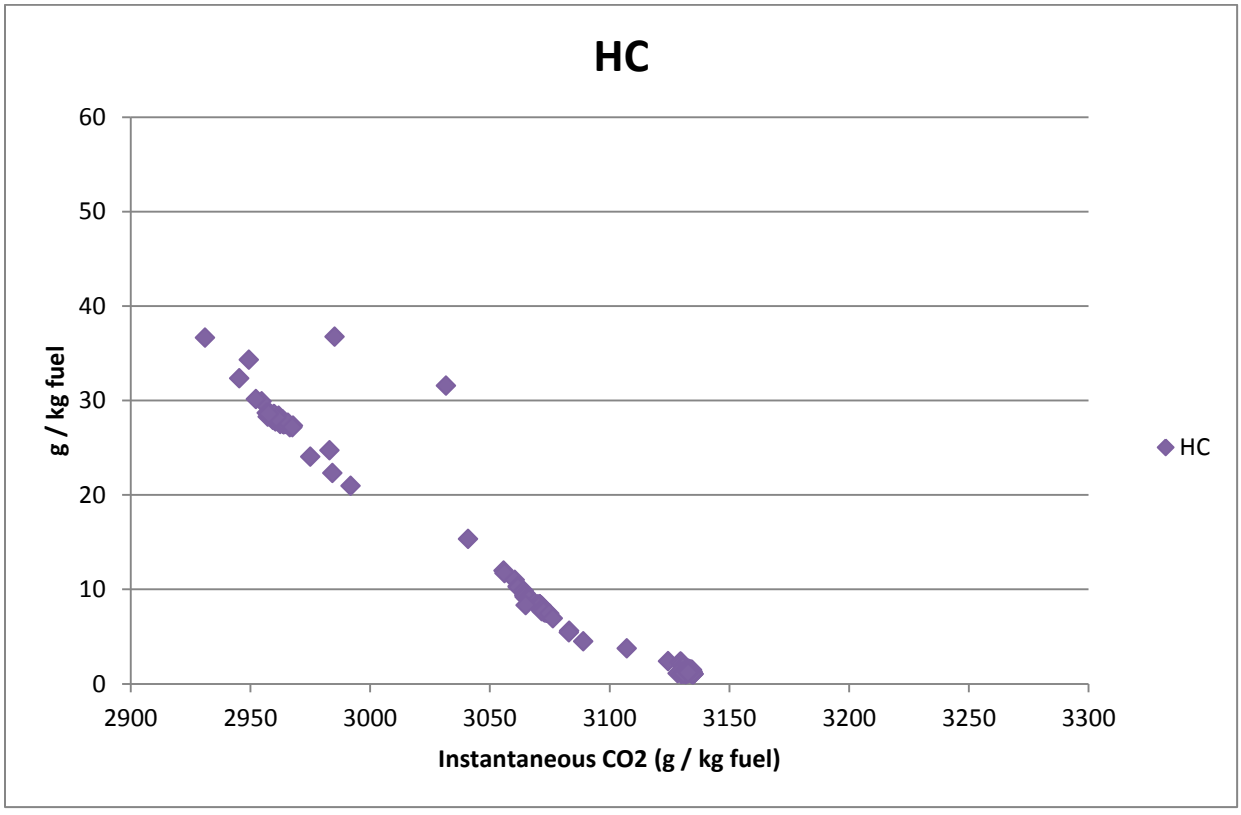

HC
g / kg fuel
Run Time (min)
HC
0
10
20
30
40
50
60
0
2
4
6
8
10
12
14
16
18
20


EGT
600
500
400
300
200
100
0
degrees C
0
5
10
15
20
Run Time (min)
EGT

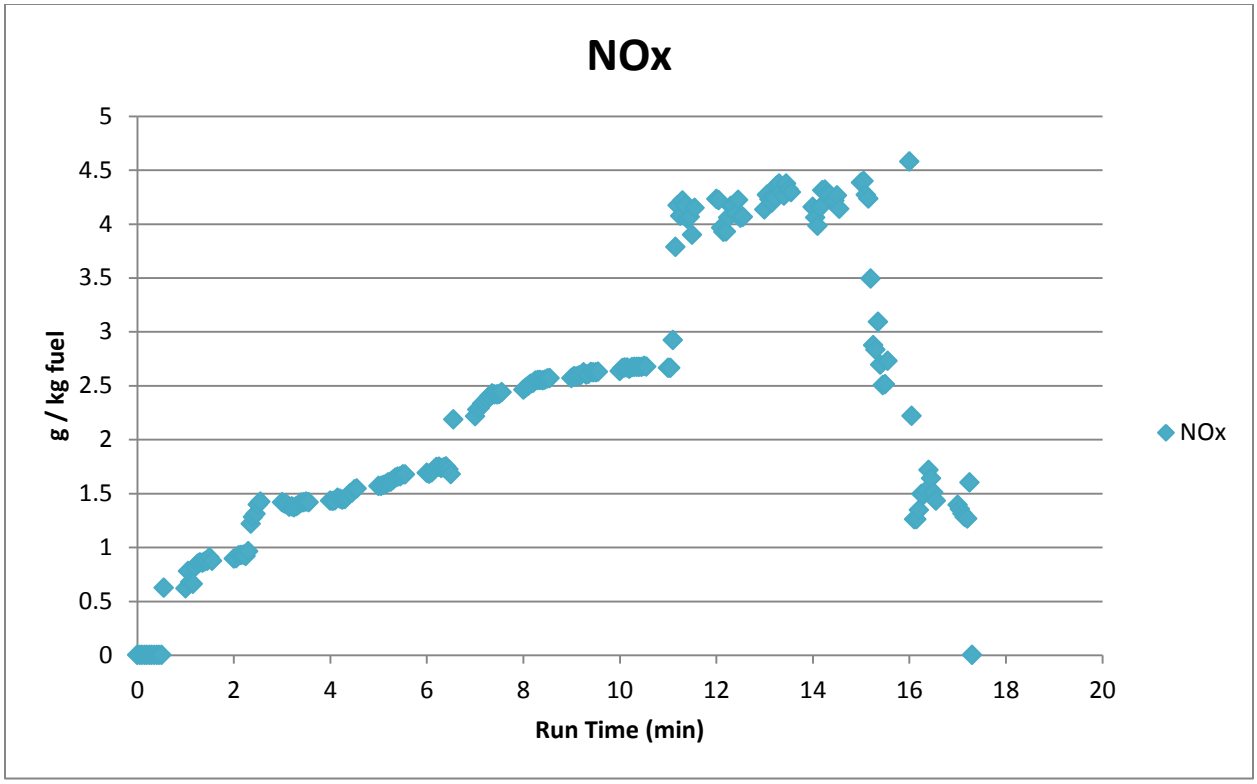

CO2
3300
3250
3200
3150
3100
3050
3000
2950
2900
g / kg fuel
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
CO2

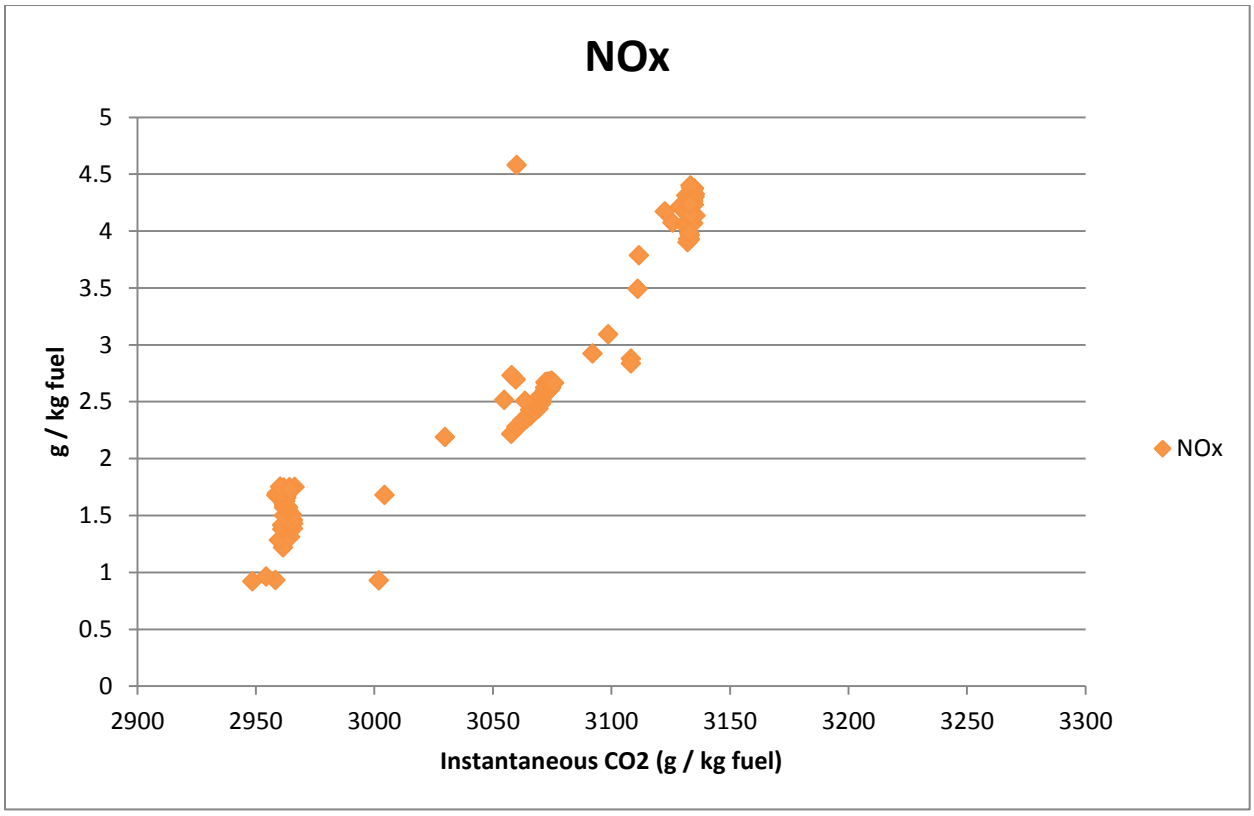

CO
120
100
80
60
40
20
0
g / kg fuel
2900
2950
3000
3050
3100
3150
3200
3250
3300
Instantaneous CO2 (g / kg fuel)
CO


NO
4
3.5
3
2.5
2
1.5
1
0.5
0
g / kg fuel
2900
2950
3000
3050
3100
3150
3200
3250
3300
Instantaneous CO2 (g / kg fuel)
NO

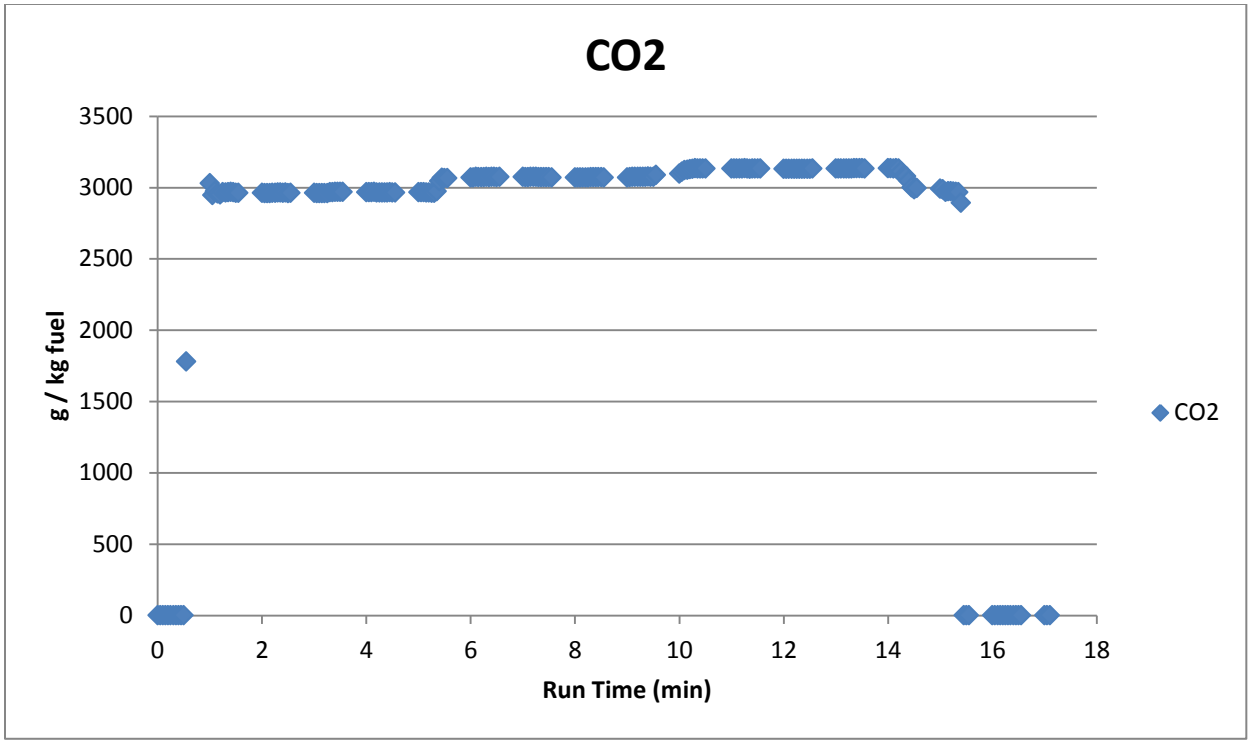

HC
60
50
40
30
20
10
0
g / kg fuel
2900
2950
3000
3050
3100
3150
3200
3250
3300
Instantaneous CO2 (g / kg fuel)
HC

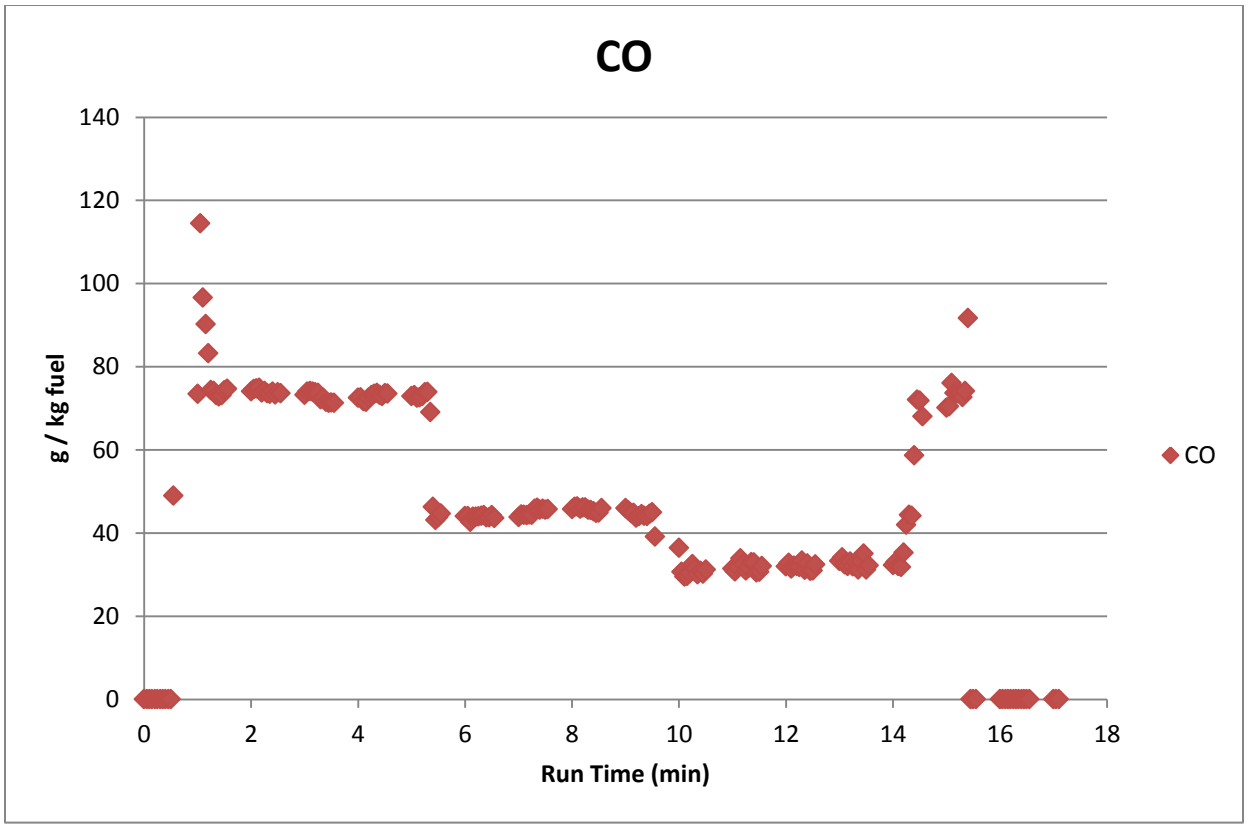
Salina4 HRJ Combined NOx 10/24/2012 PT6

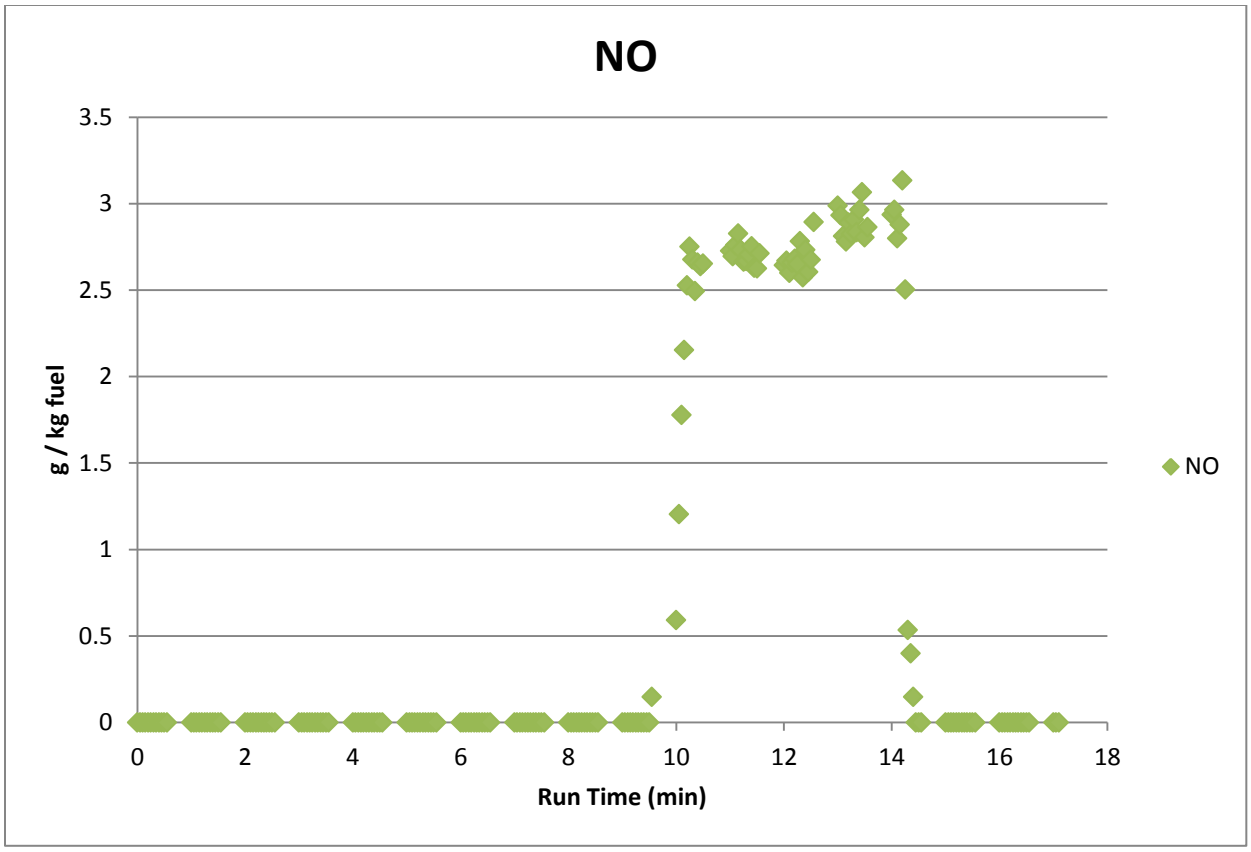


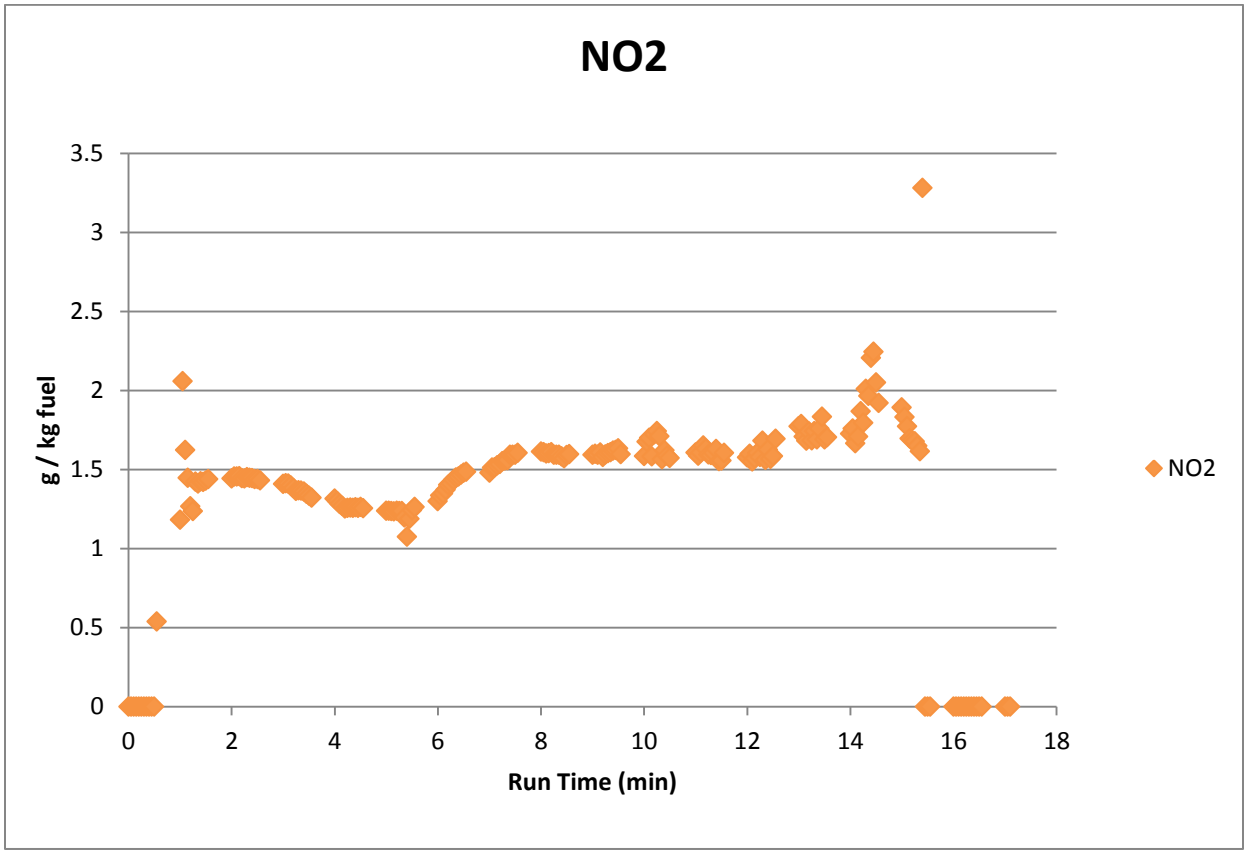


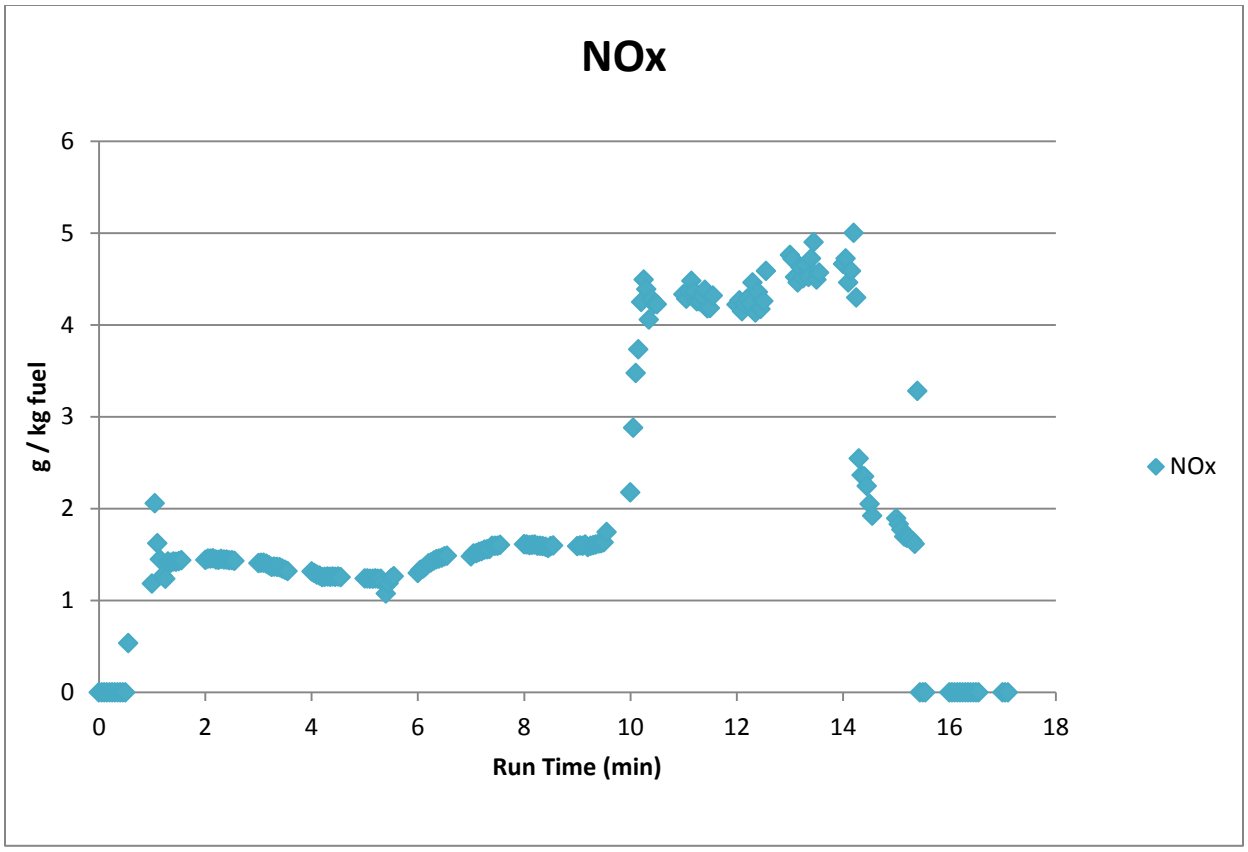
Salina4 FT NCF 10/24/2012 PT6

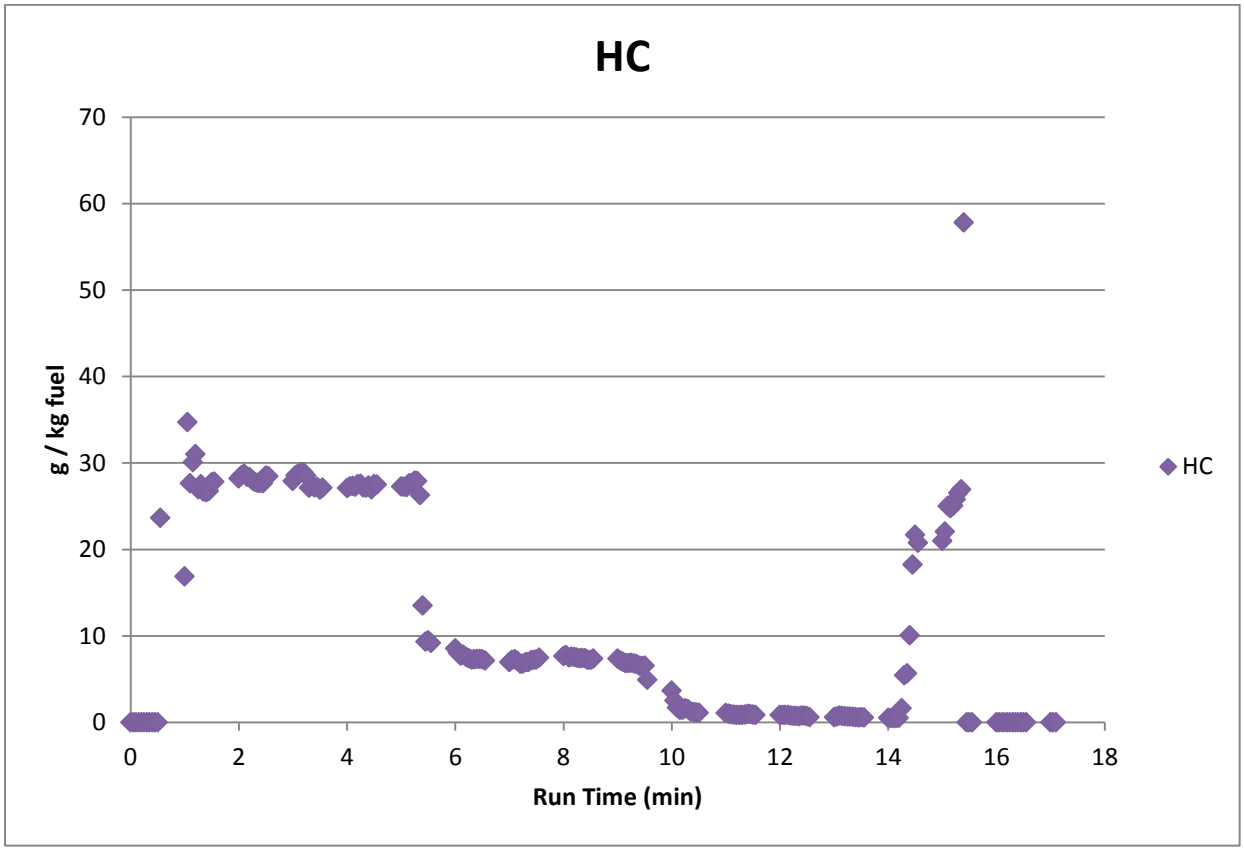


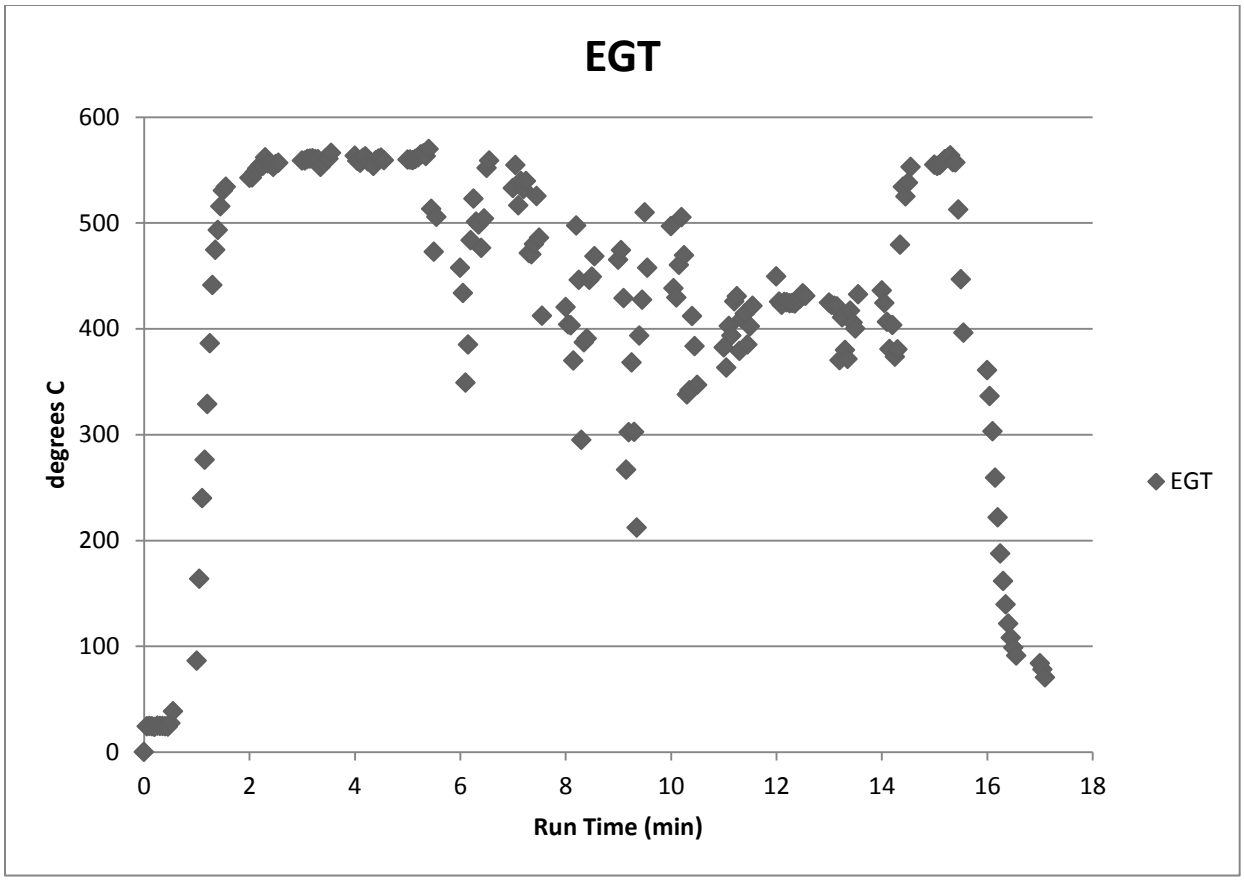


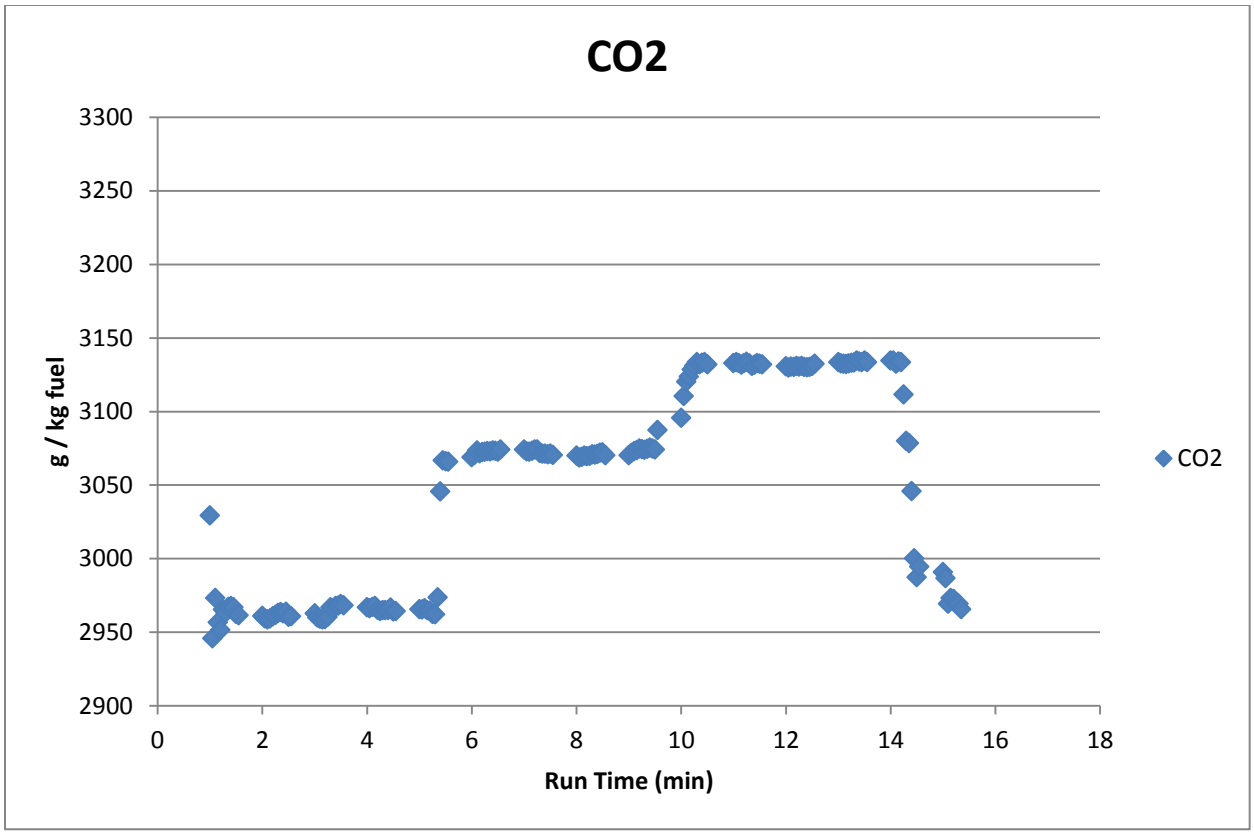

NO
3.5
3
2.5
2
1.5
1
0.5
0
g / kg fuel
0
2
4
6
8
10
12
14
16
18
Run Time (min)
NO

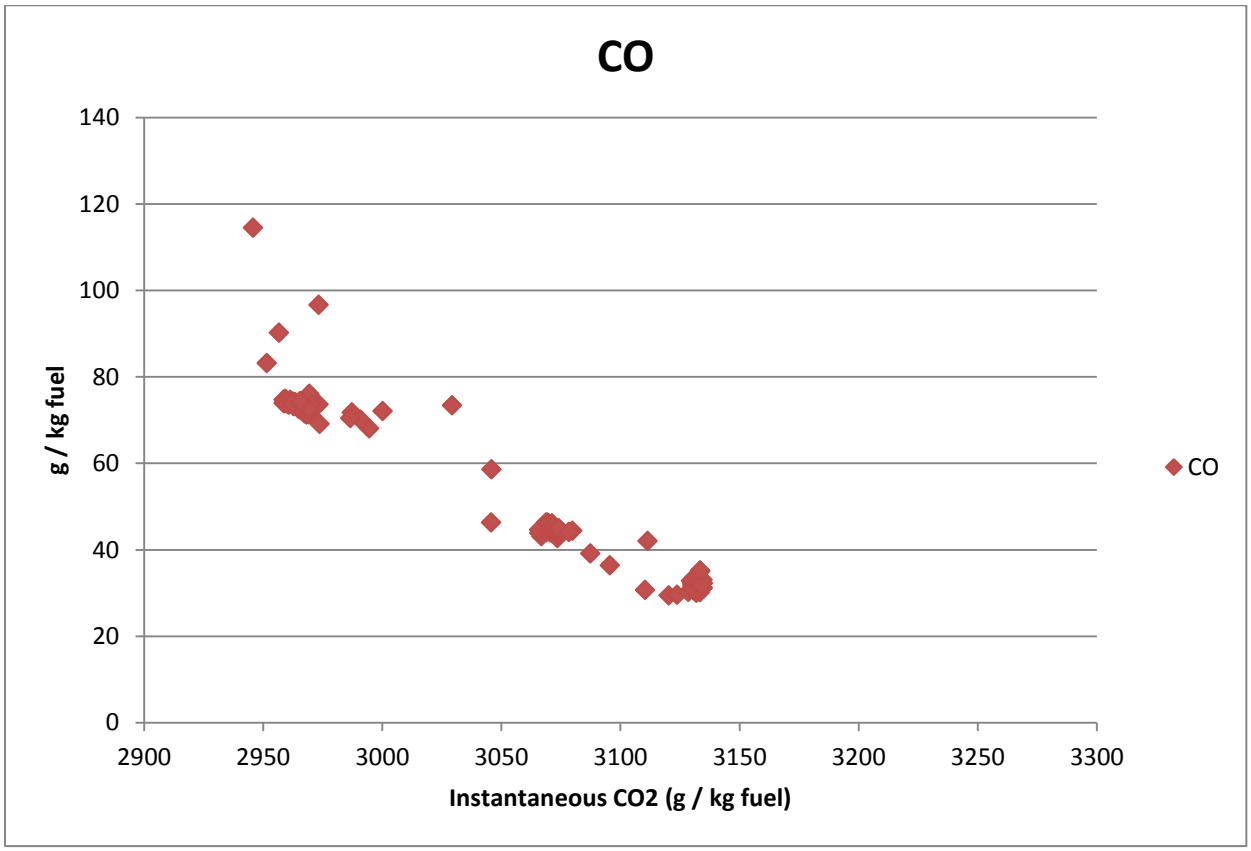

NO2
3.5
3
2.5
2
1.5
1
0.5
0
g / kg fuel
0
2
4
6
8
10
12
14
16
18
Run Time (min)
NO2

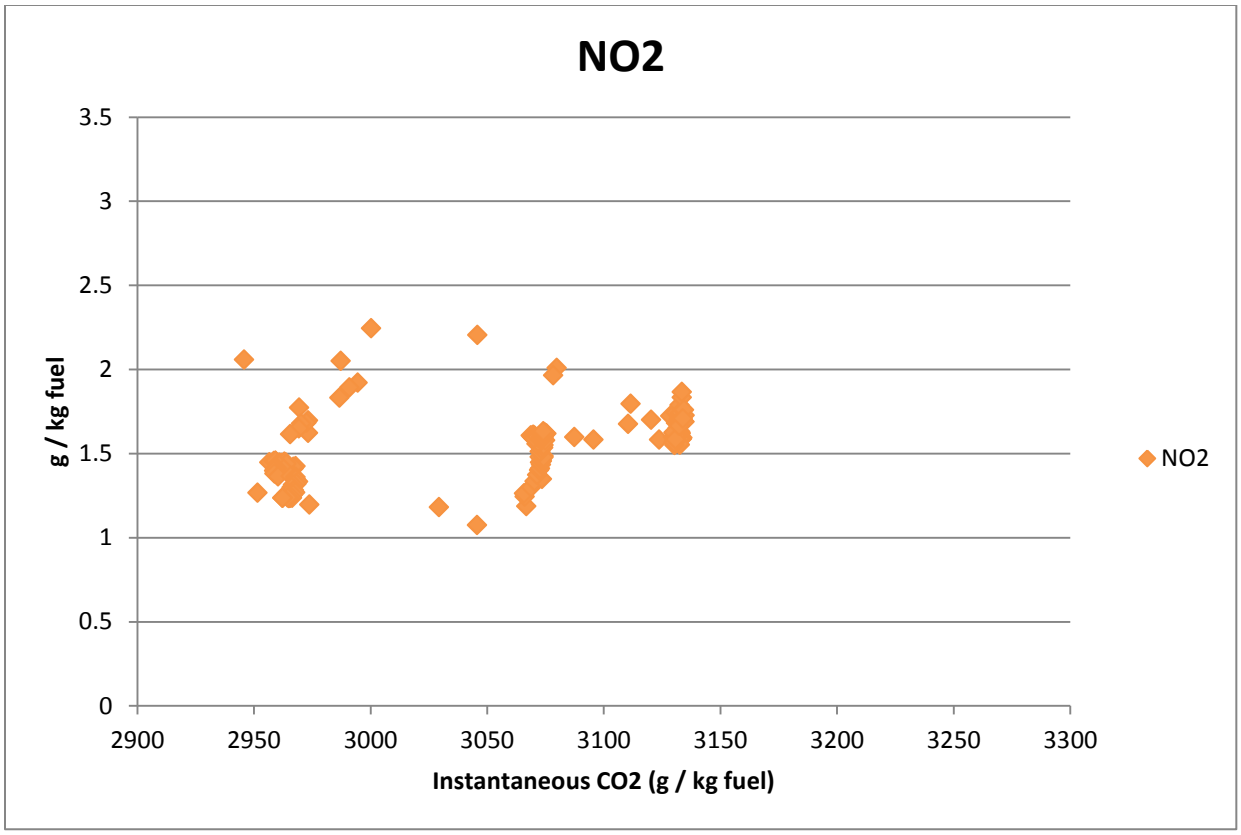

NOx
g / kg fuel
0
1
2
3
4
5
6
0
2
4
6
8
10
12
14
16
18
Run Time (min)
NOx

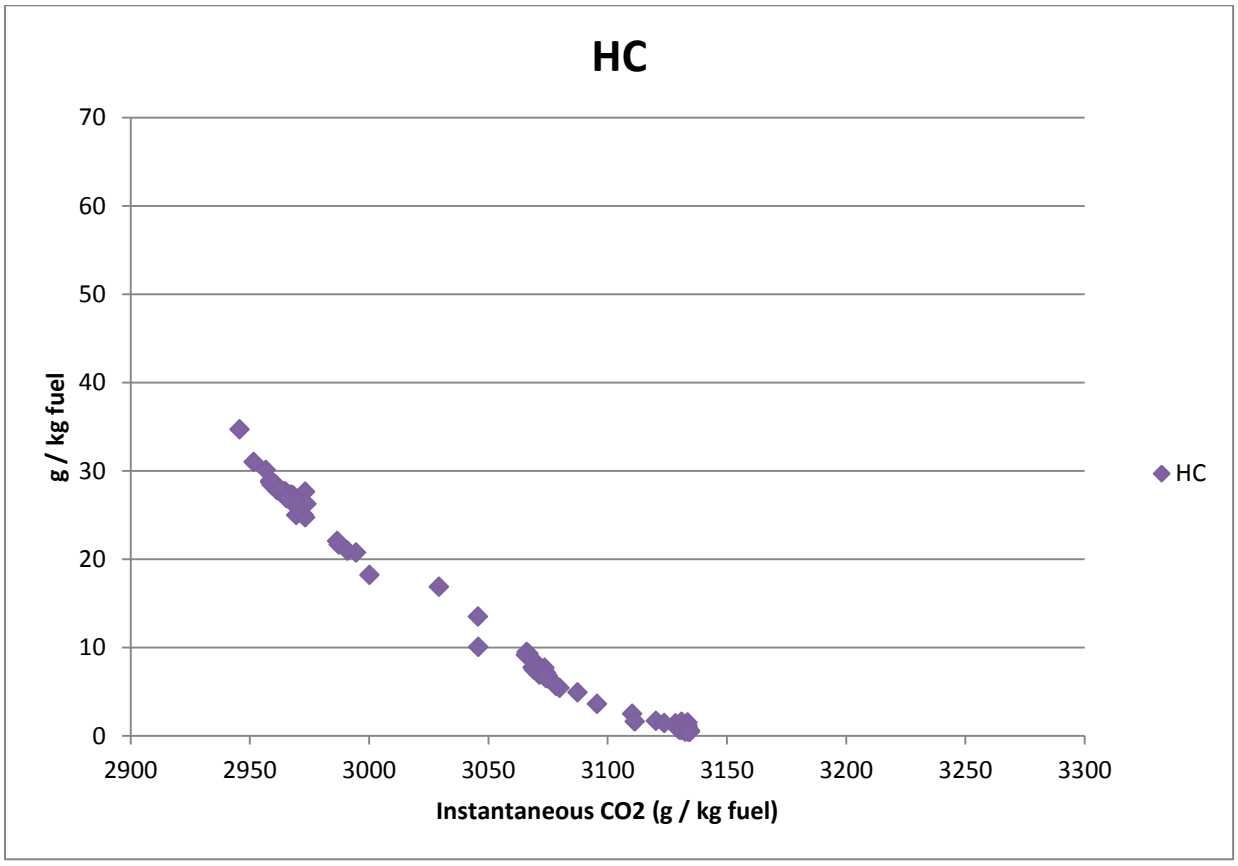

HC
g / kg fuel
0
10
20
30
40
50
60
70
0
2
4
6
8
10
12
14
16
18
Run Time (min)
HC


EGT
600
500
400
300
200
100
0
degrees C
0
2
4
6
8
10
12
14
16
18
Run Time (min)
EGT

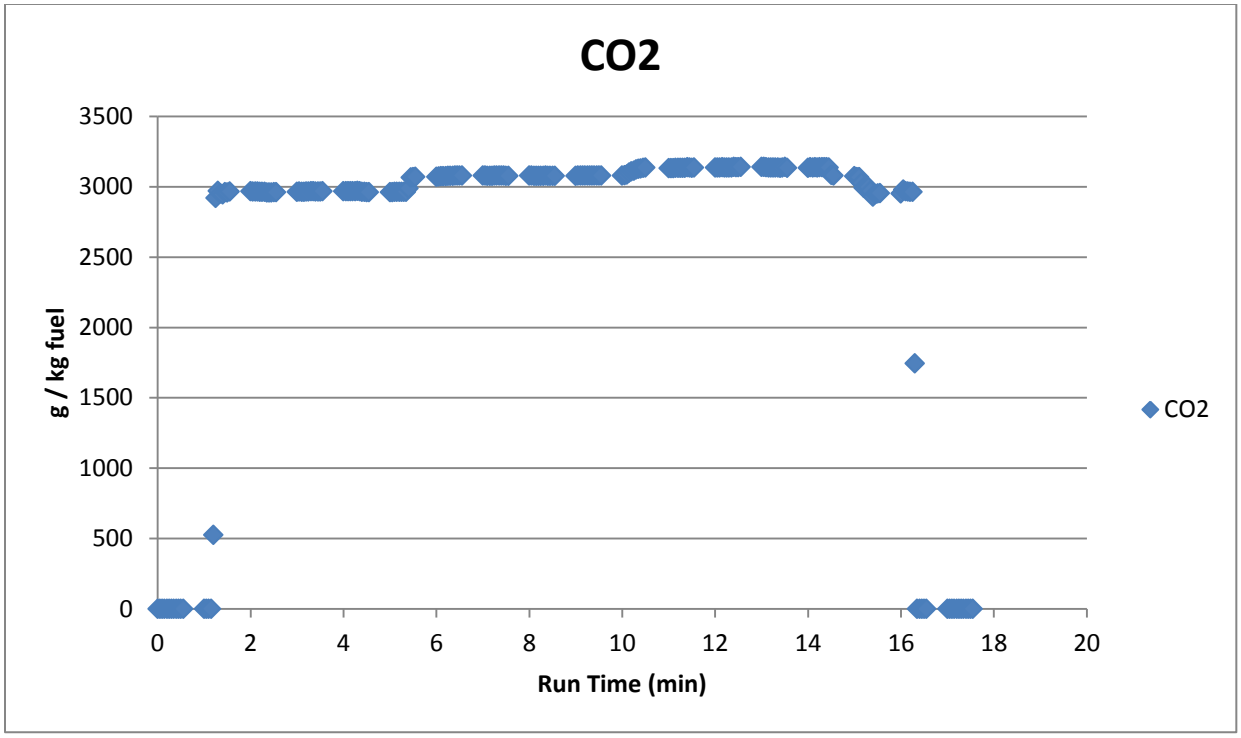

CO2
3300
3250
3200
3150
3100
3050
3000
2950
2900
g / kg fuel
0
2
4
6
8
10
12
14
16
18
Run Time (min)
CO2

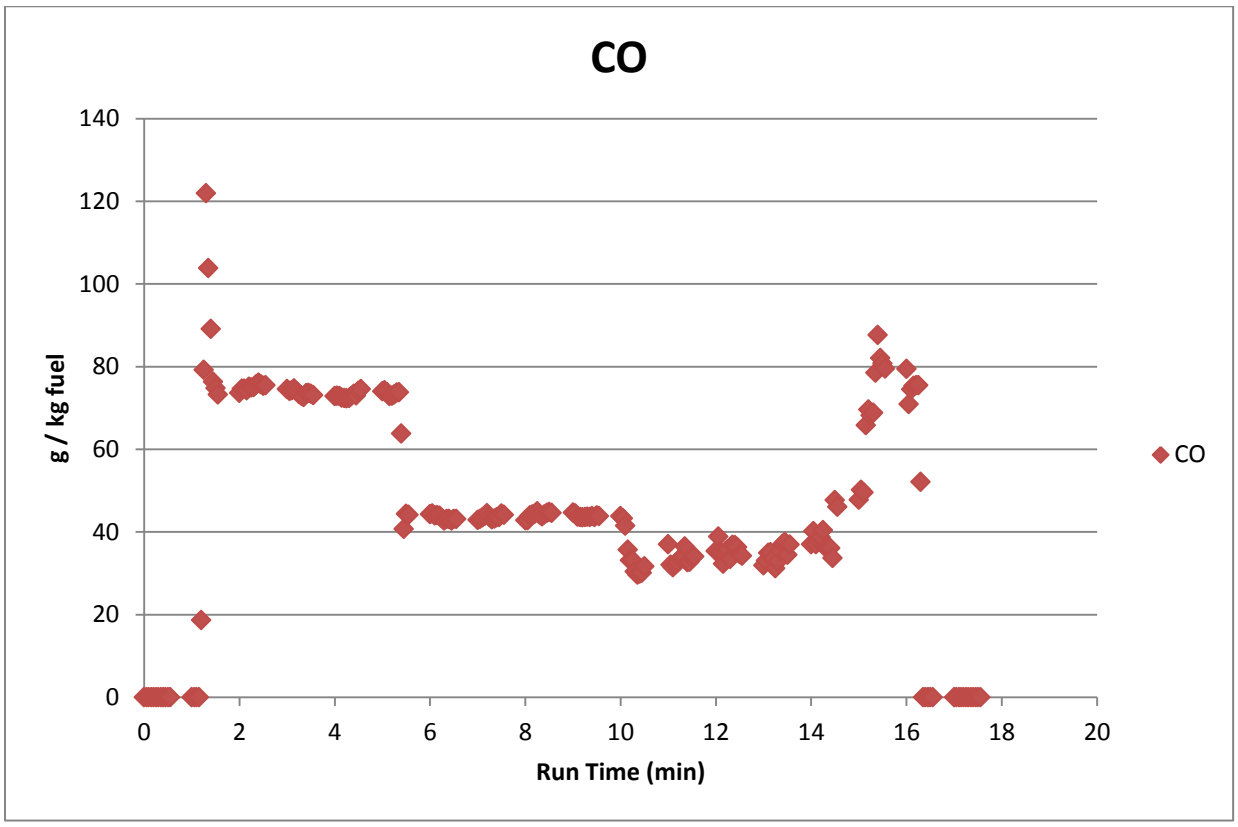

CO
140
120
100
80
60
40
20
0
g / kg fuel
2900
2950
3000
3050
3100
3150
3200
3250
3300
Instantaneous CO2 (g / kg fuel)
CO

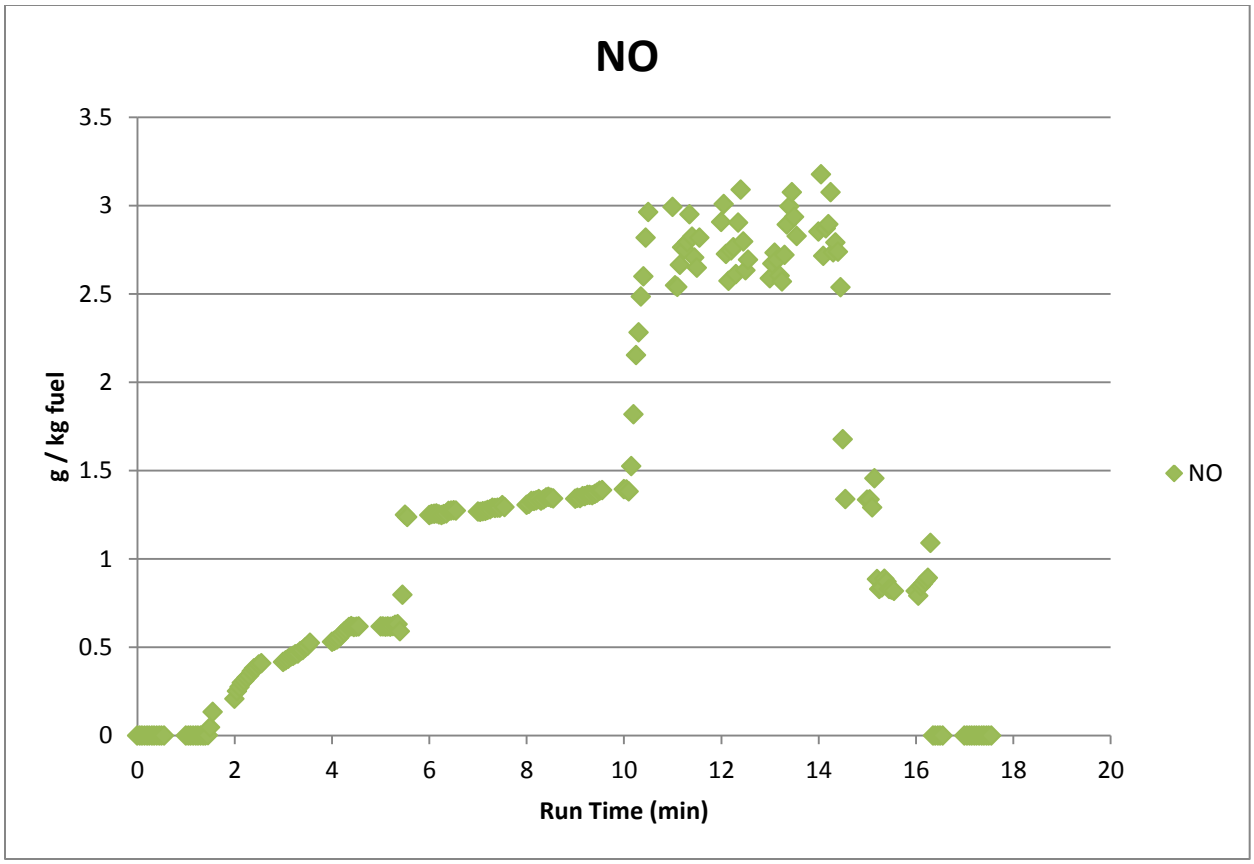

NO2
3.5
3
2.5
2
1.5
1
0.5
0
g / kg fuel
2900
2950
3000
3050
3100
3150
3200
3250
3300
Instantaneous CO2 (g / kg fuel)
NO2

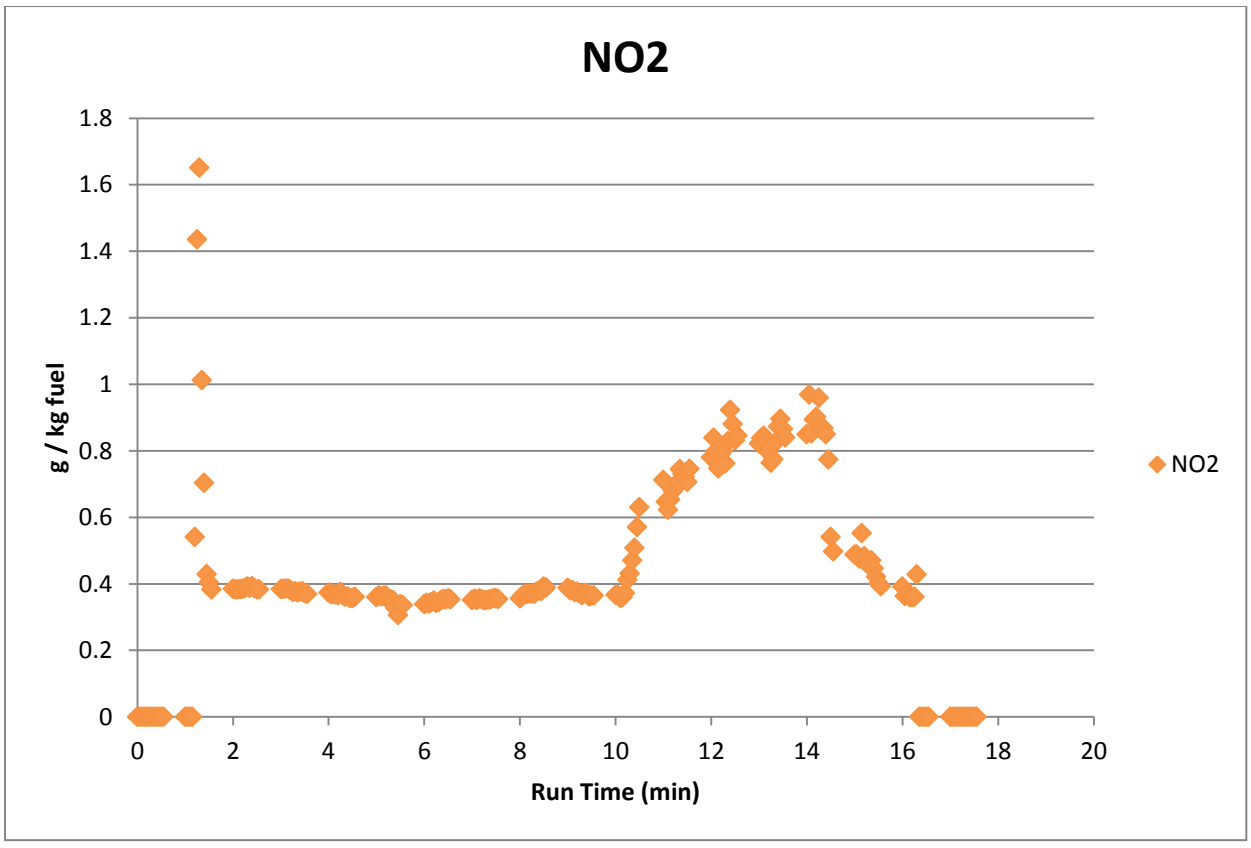

HC
70
60
50
40
30
20
10
0
g / kg fuel
2900
2950
3000
3050
3100
3150
3200
3250
3300
Instantaneous CO2 (g / kg fuel)
HC

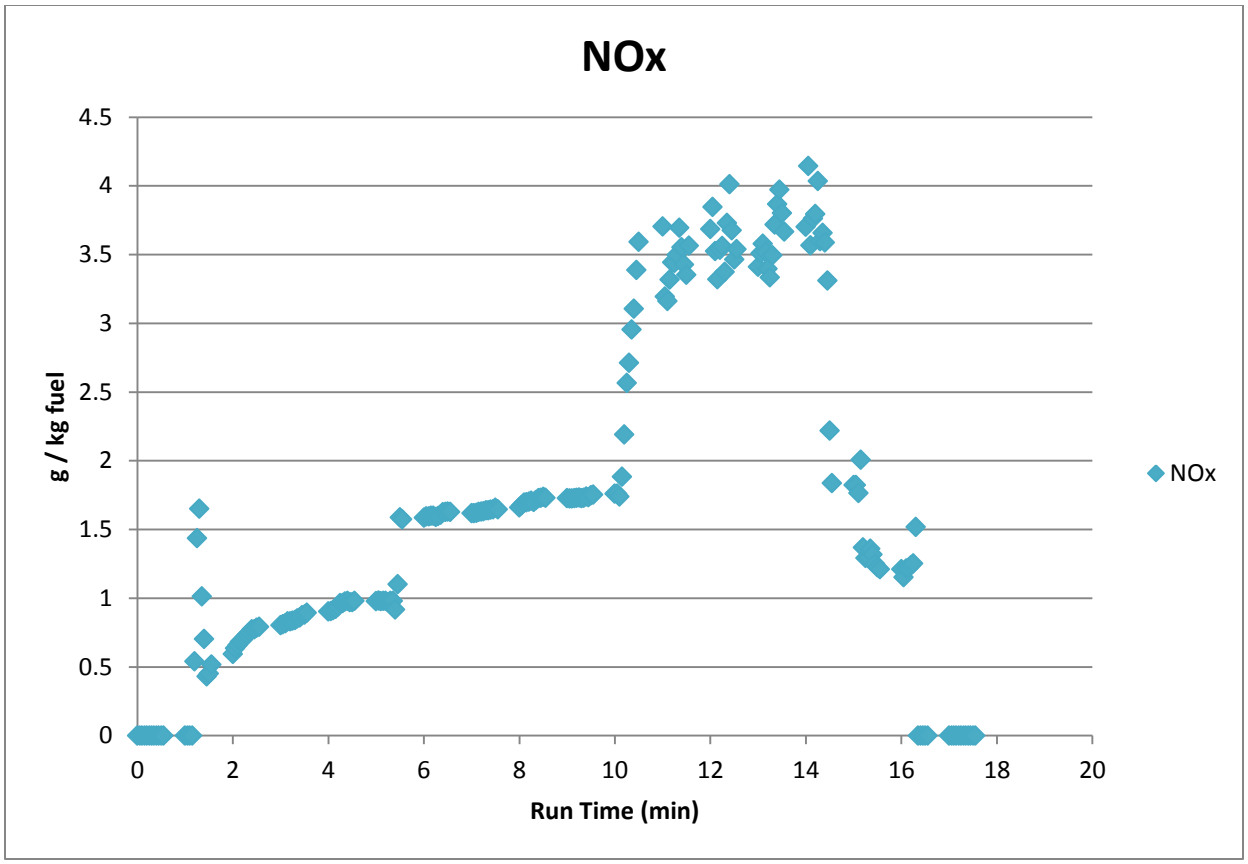
Salina4 FT CF 10/24/2012 PT6

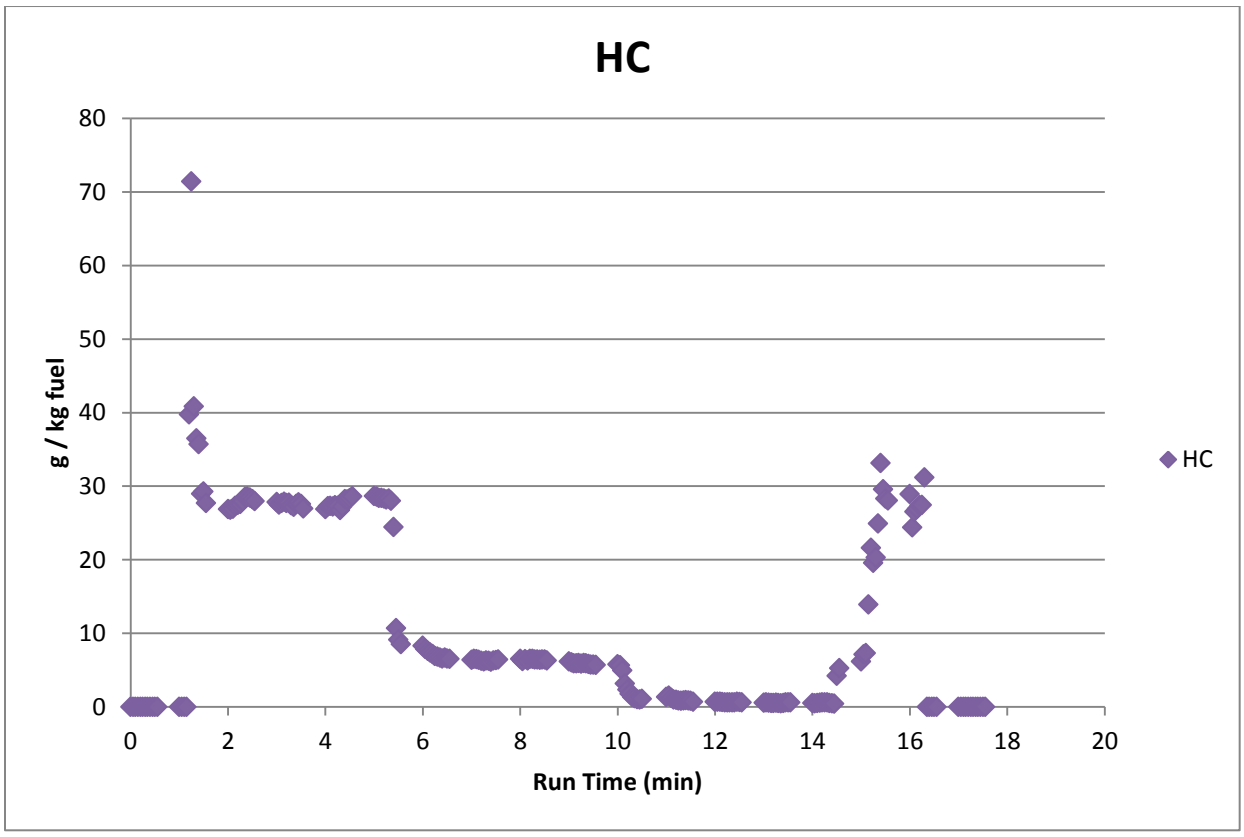


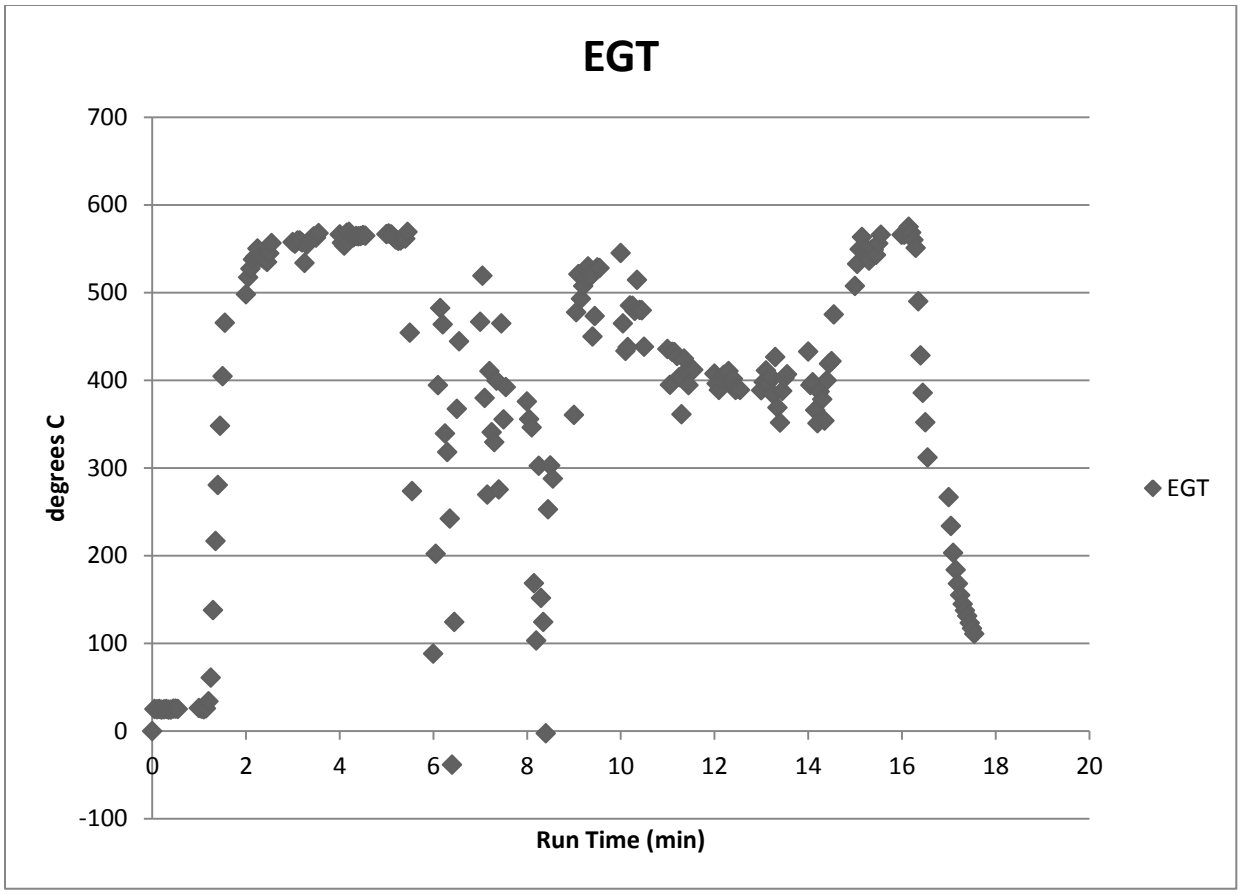


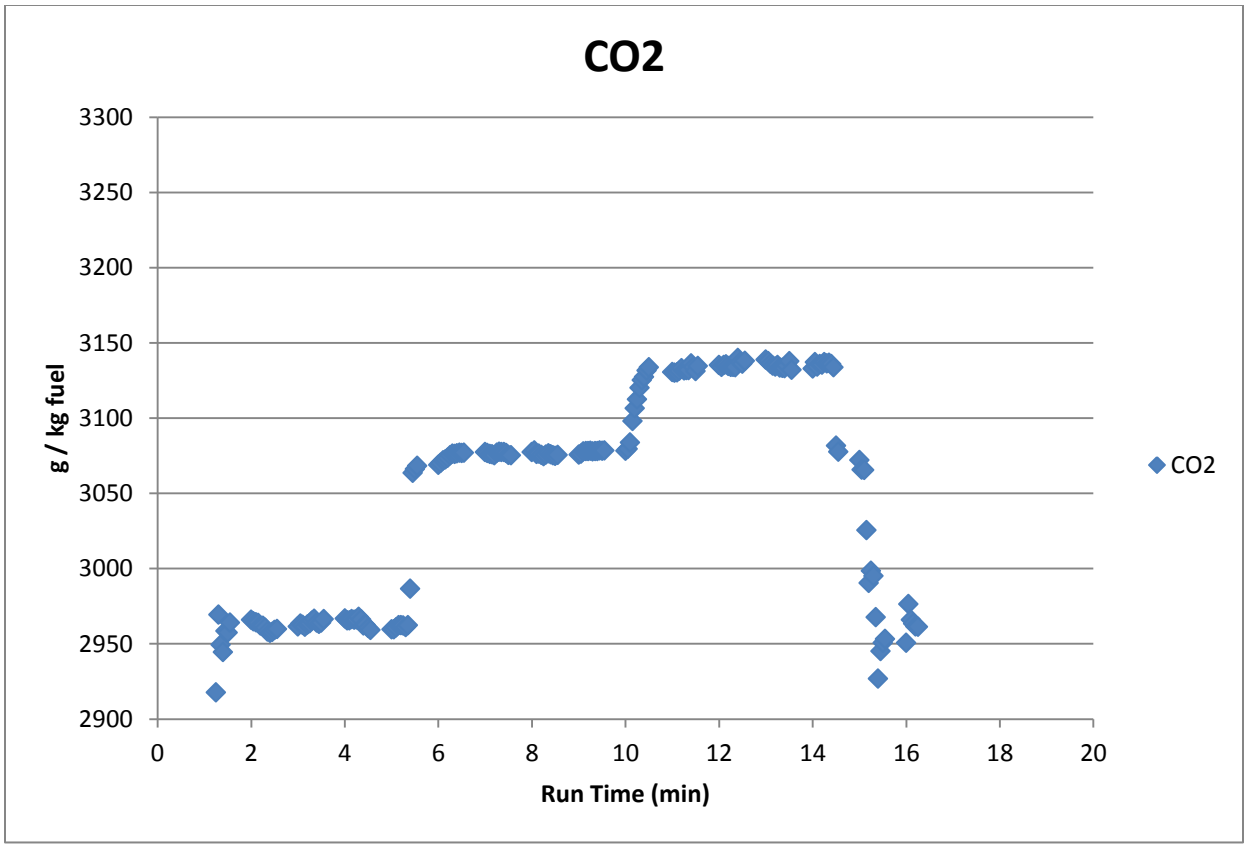

NO
3.5
3
2.5
2
1.5
1
0.5
0
g / kg fuel
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
NO

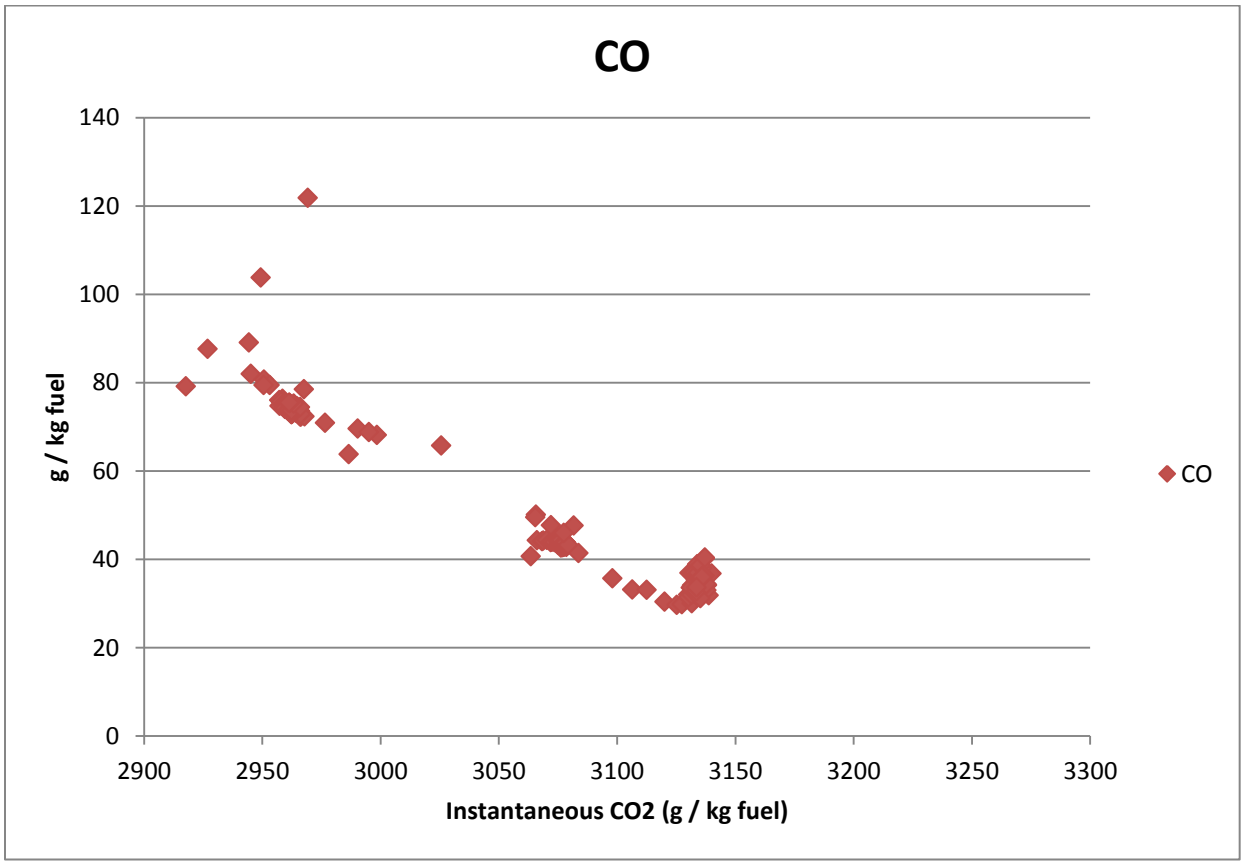

NO2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
g / kg fuel
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
NO2

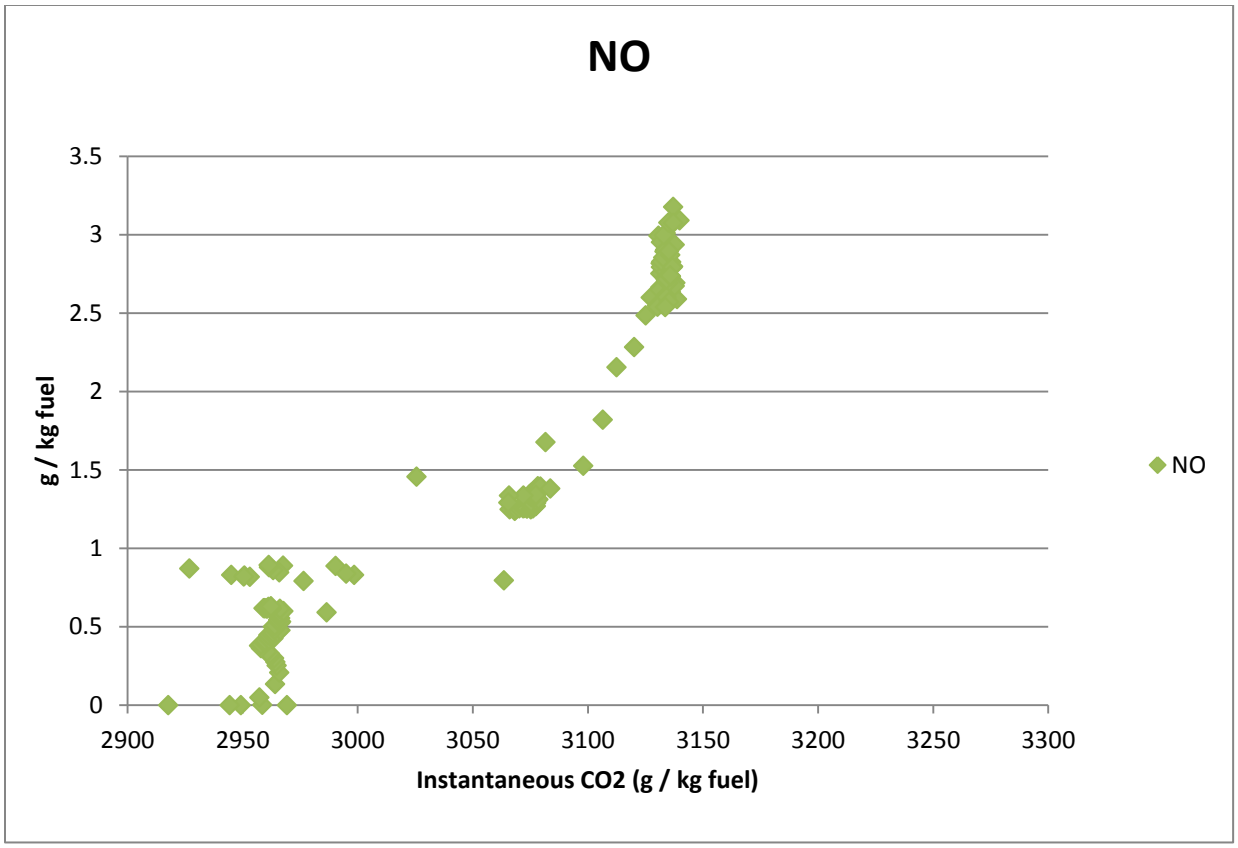

NOx
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
g / kg fuel
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
NOx

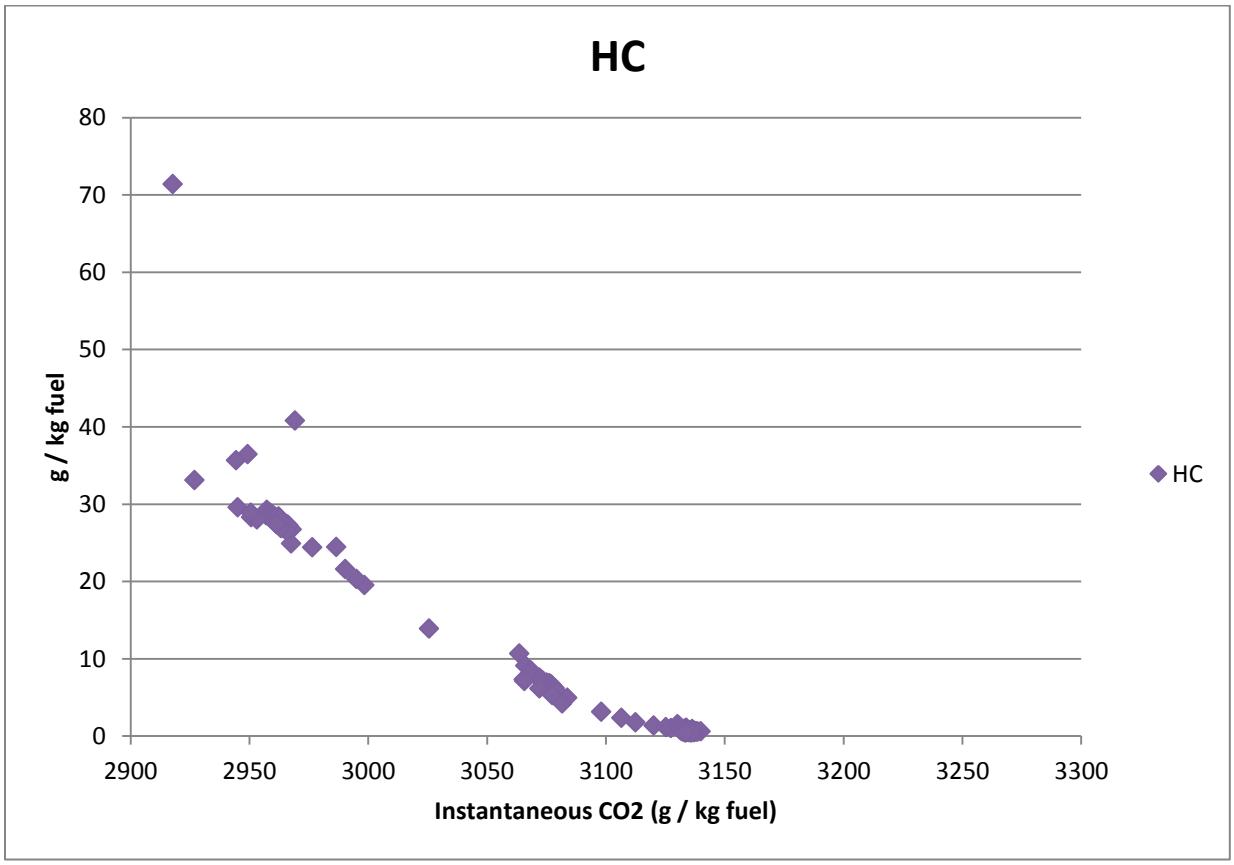

HC
80
70
60
50
40
30
20
10
0
g / kg fuel
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
HC


EGT
700
600
500
400
300
200
100
0
-100
degrees C
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
EGT

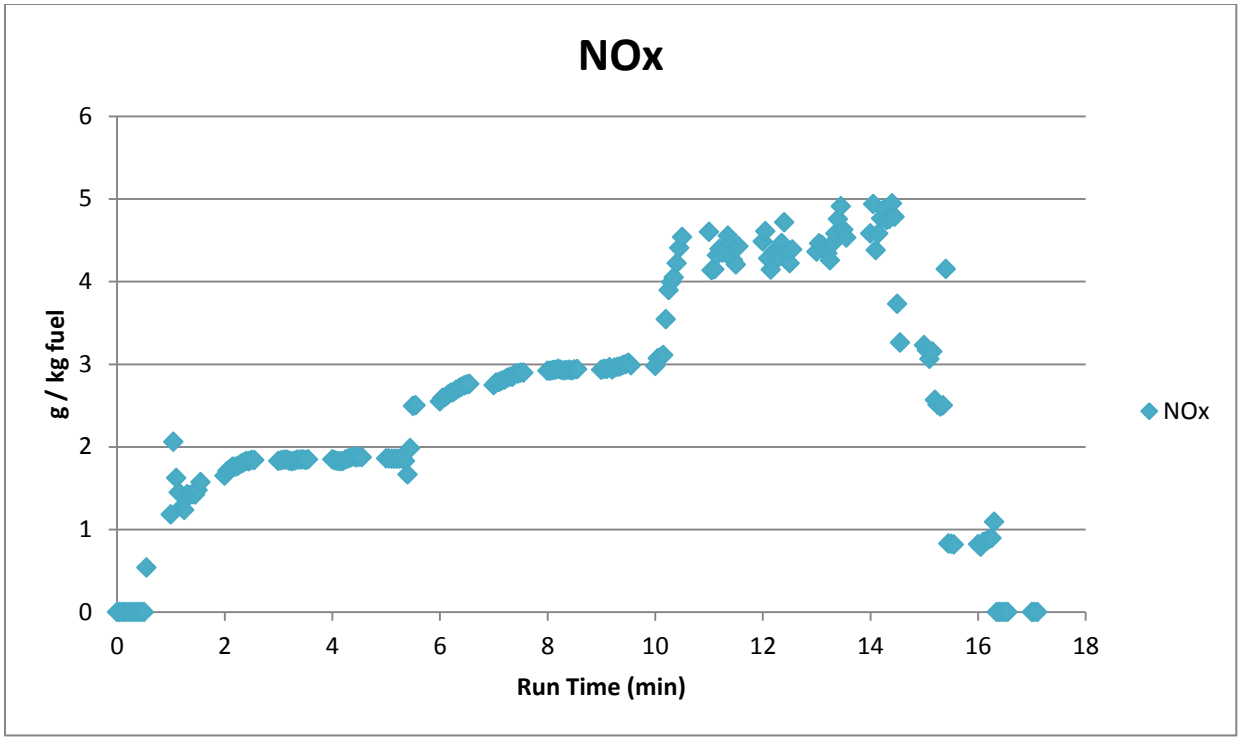

CO2
3300
3250
3200
3150
3100
3050
3000
2950
2900
g / kg fuel
0
2
4
6
8
10
12
14
16
18
20
Run Time (min)
CO2

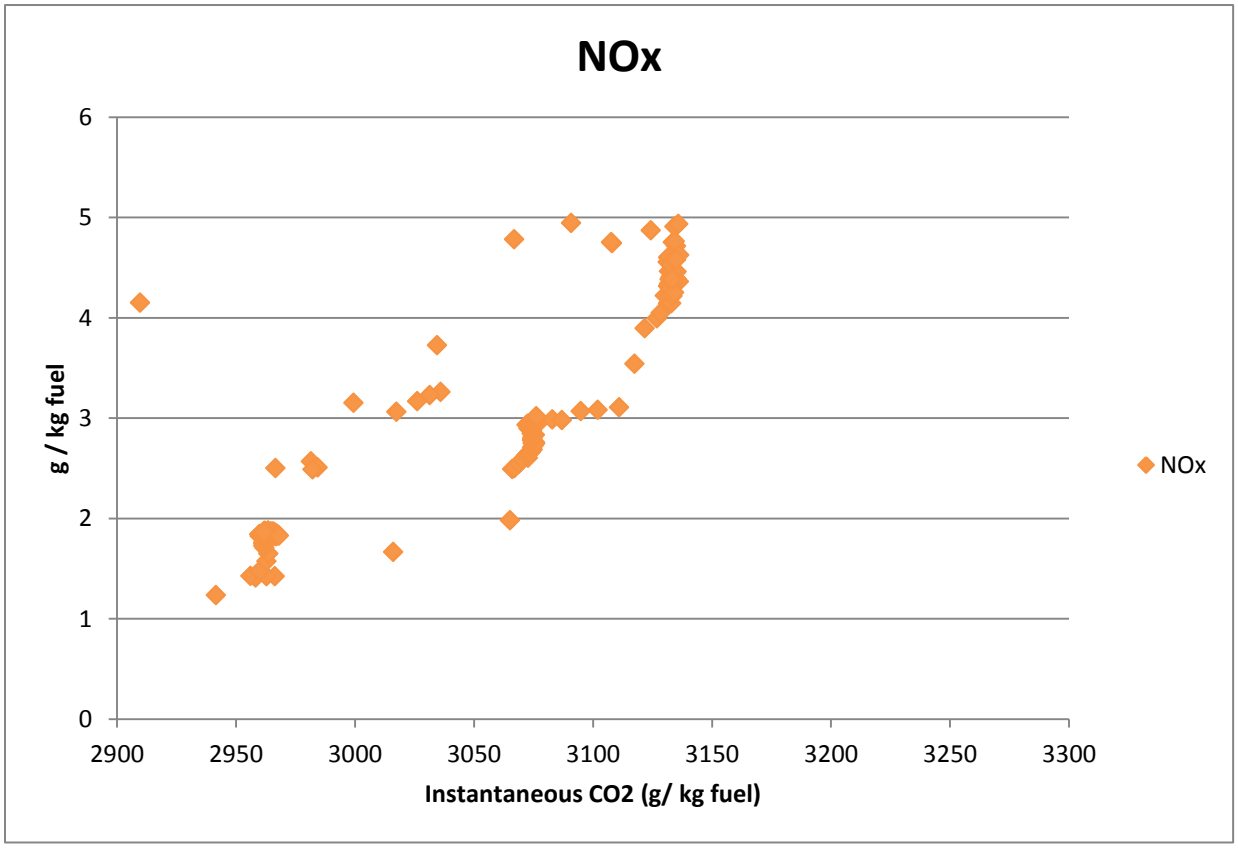

CO
140
120
100
80
60
40
20
0
g / kg fuel
2900
2950
3000
3050
3100
3150
3200
3250
3300
Instantaneous CO2 (g / kg fuel)
CO


NO
3.5
3
2.5
2
1.5
1
0.5
0
g / kg fuel
2900
2950
3000
3050
3100
3150
3200
3250
3300
Instantaneous CO2 (g / kg fuel)
NO

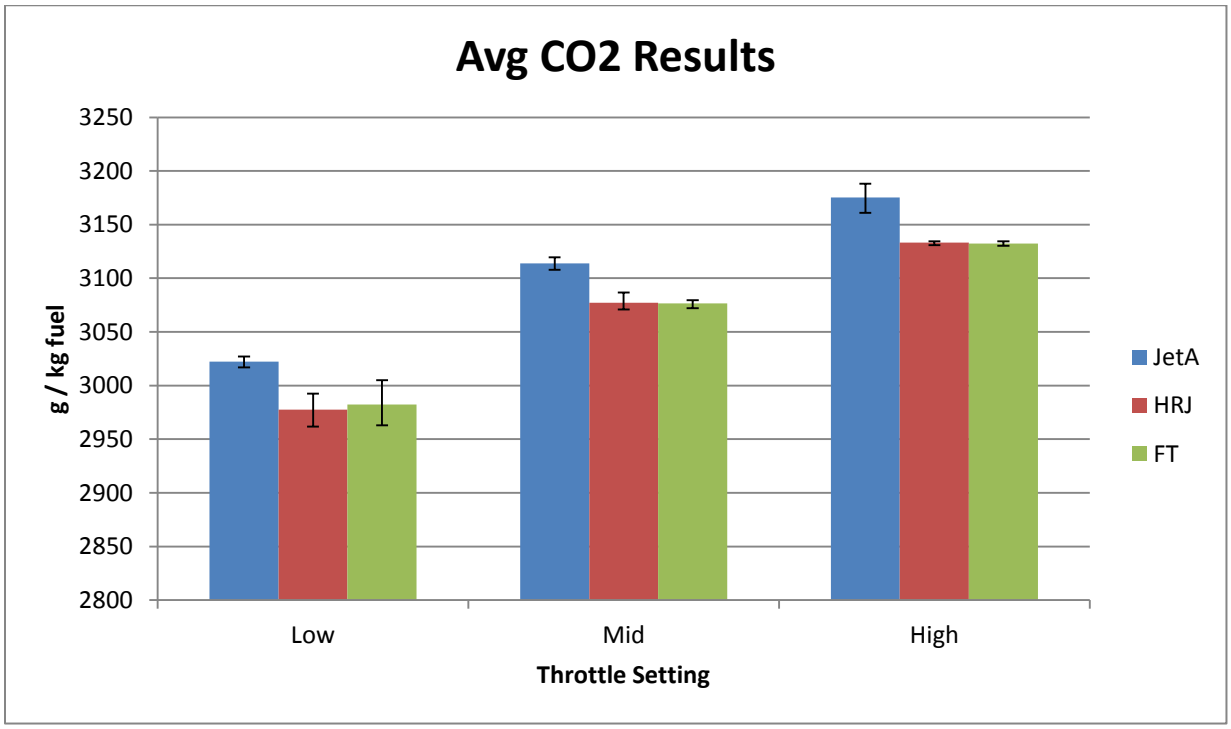

HC
80
70
60
50
40
30
20
10
0
g / kg fuel
2900
2950
3000
3050
3100
3150
3200
3250
3300
Instantaneous CO2 (g / kg fuel)
HC

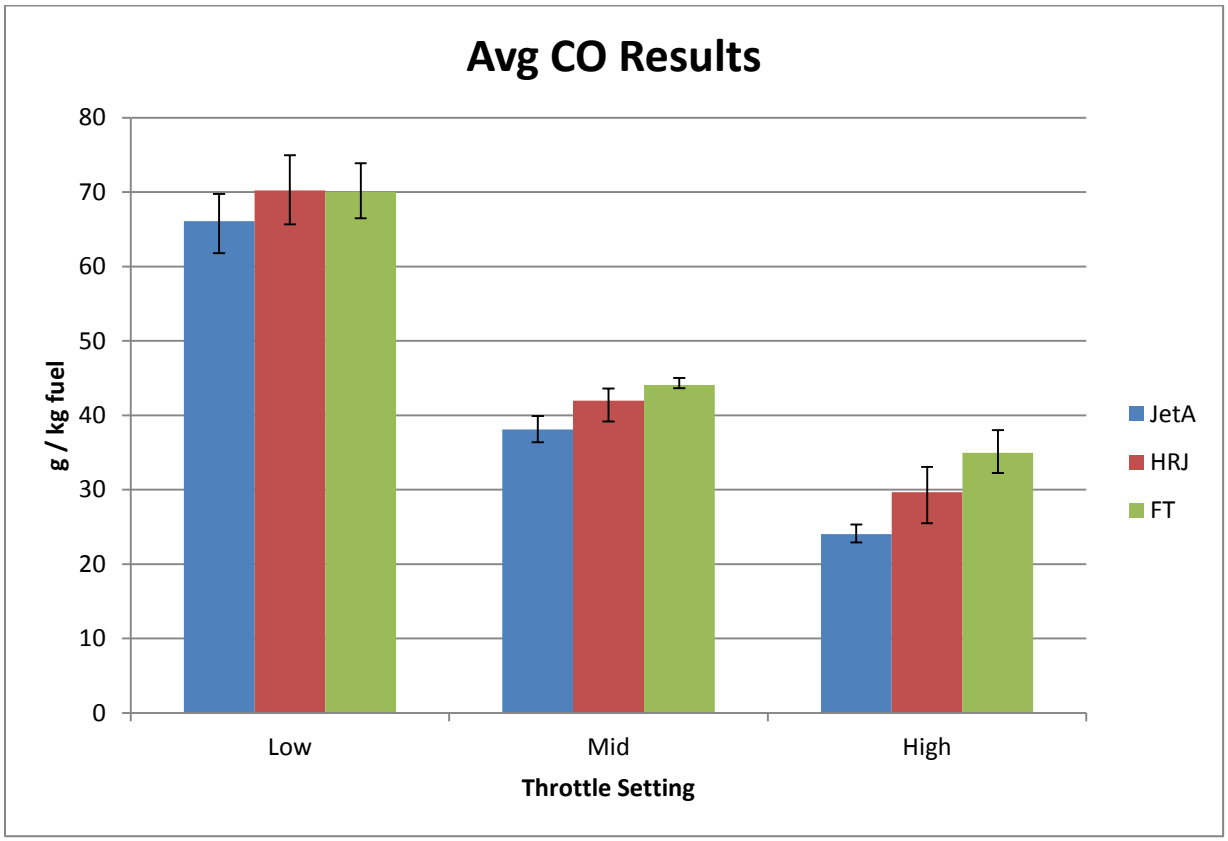
Salina4 FT Combined NOx 10/24/2012 PT6

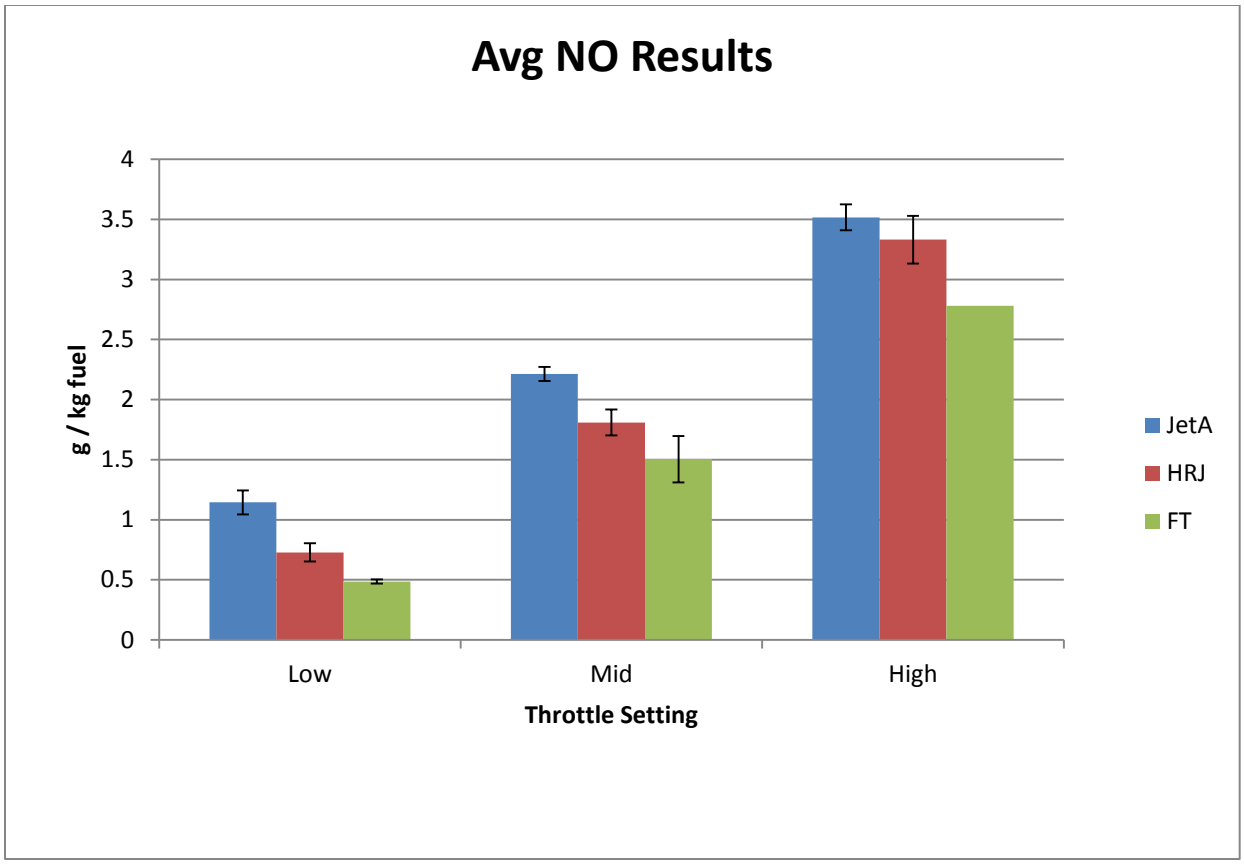


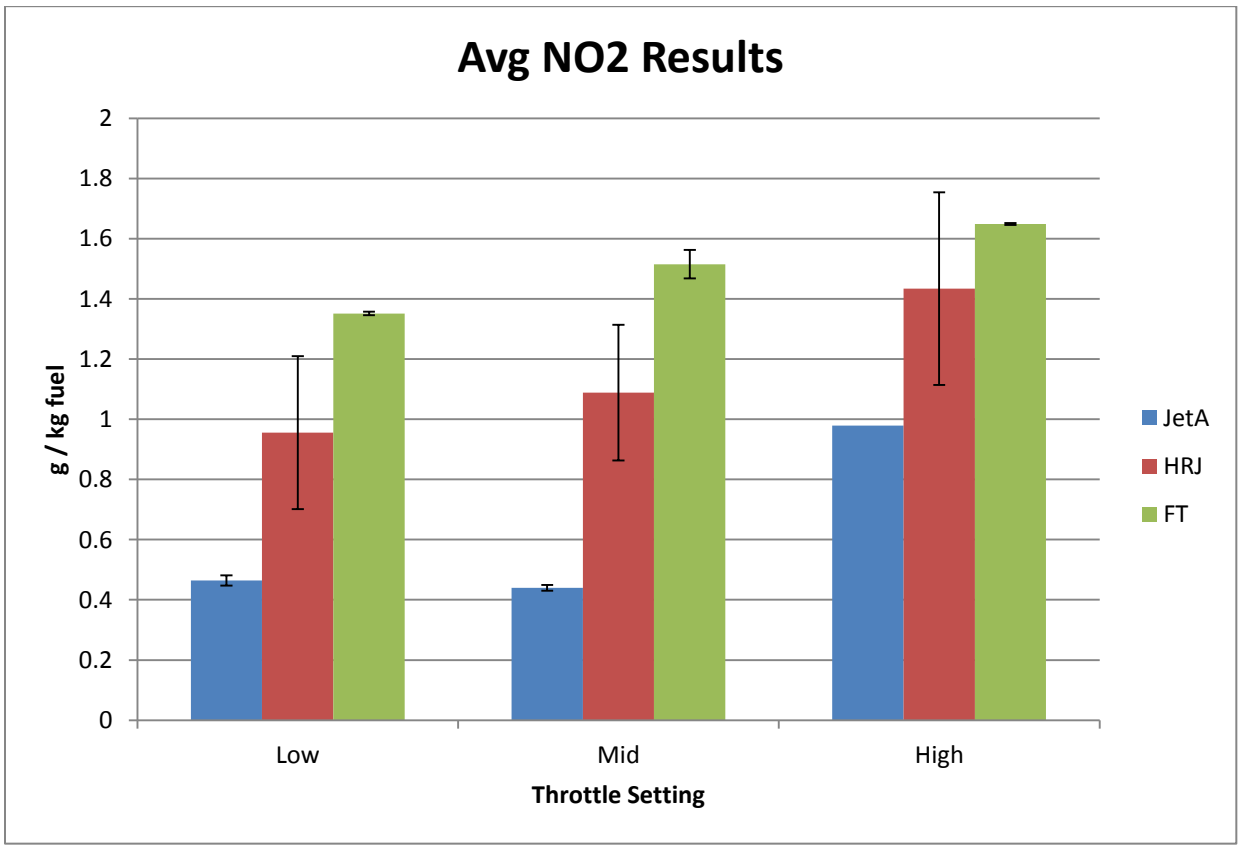


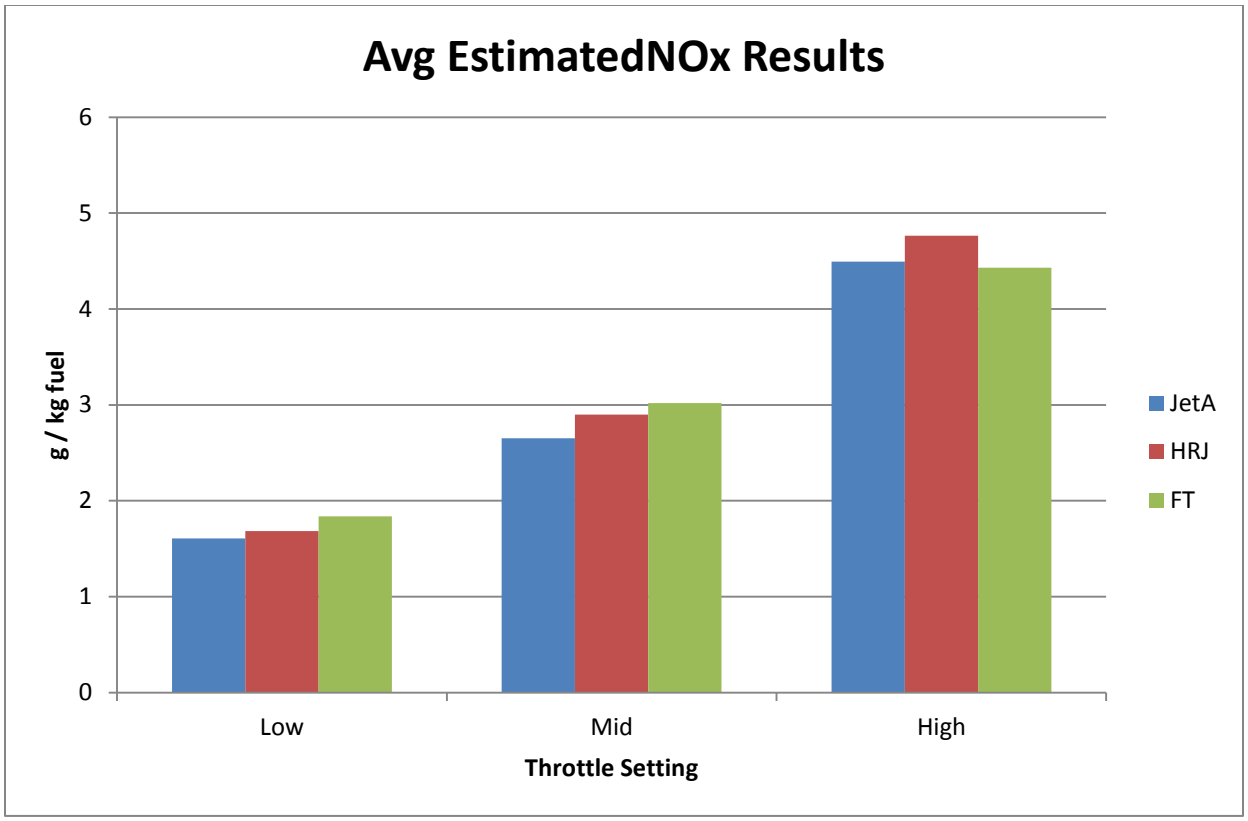
Appendix F: Average Jet A, HRJ, and FT Results for Salina3 and Salina4

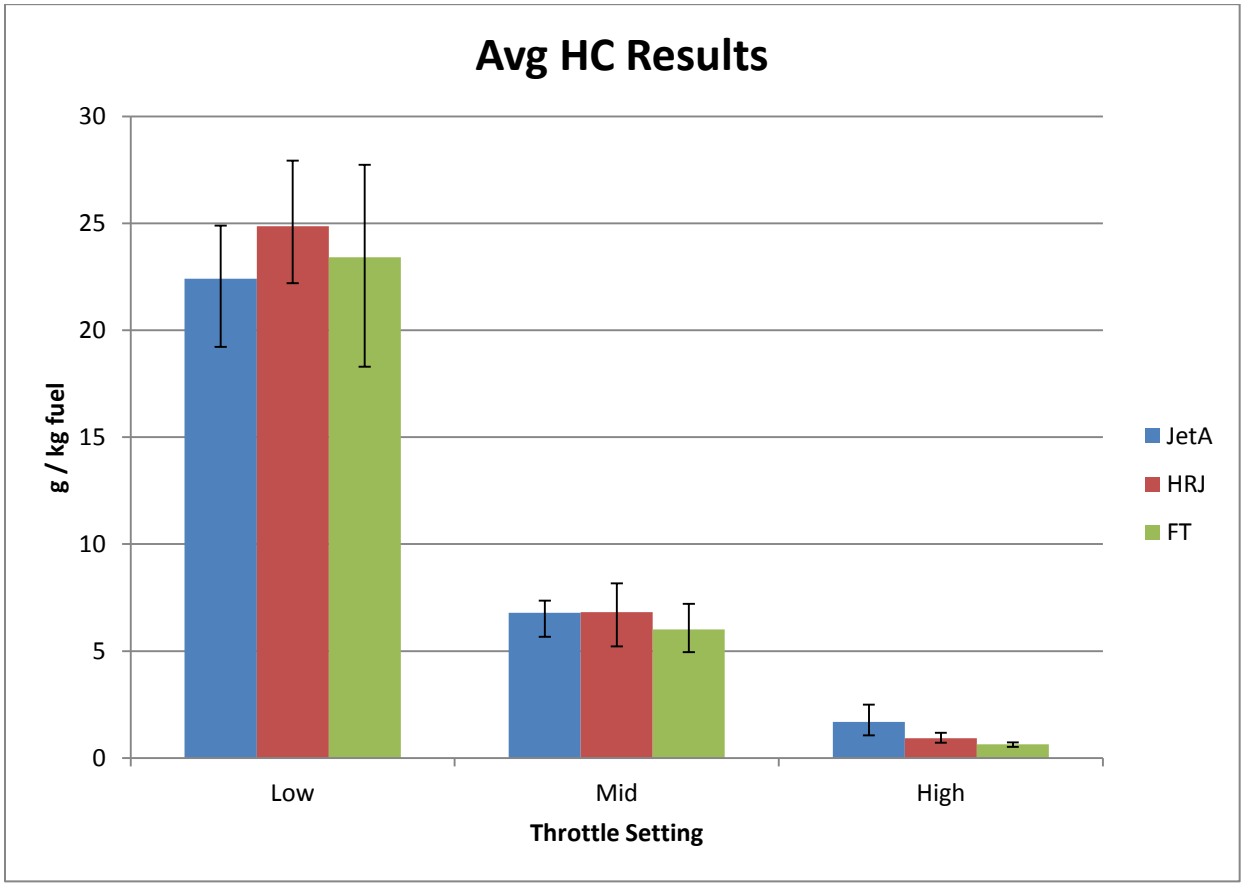


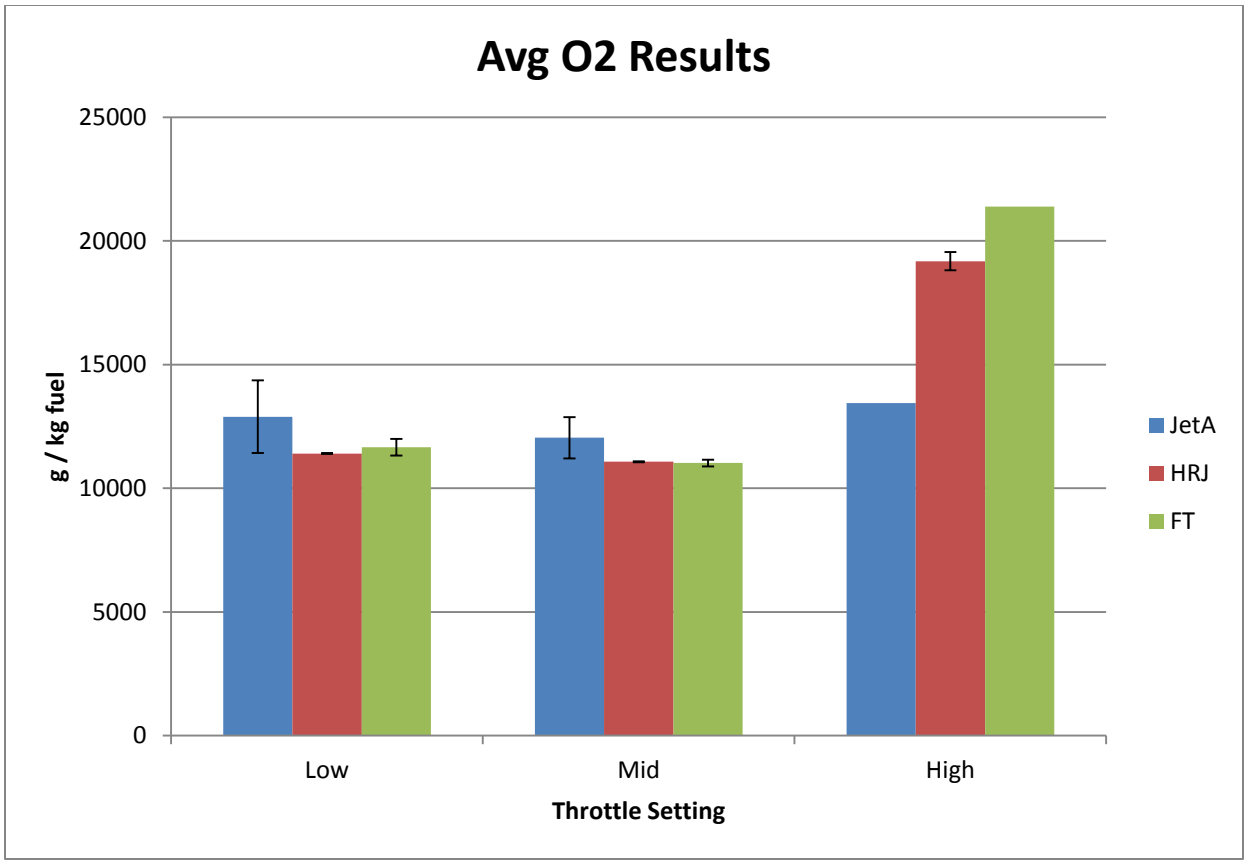


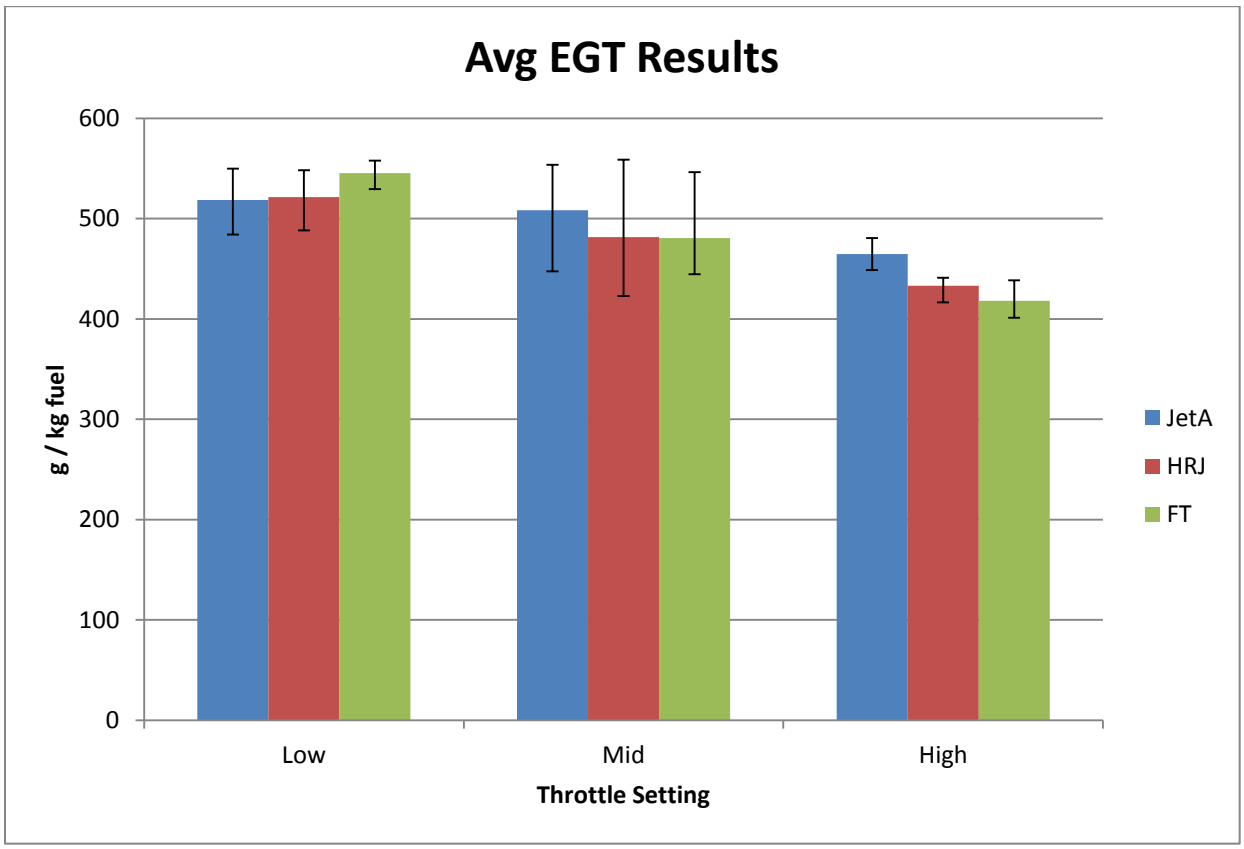

Avg NO Results
4
3.5
3
2.5
2
1.5
1
0.5
0
g / kg fuel
Low
Mid
High
Throttle Setting
JetA
HRJ
FT


Avg NO2 Results
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
g / kg fuel
Low
Mid
High
Throttle Setting
JetA
HRJ
FT


Avg EstimatedNOx Results
6
5
4
3
2
1
0
g / kg fuel
Low
Mid
High
Throttle Setting
JetA
HRJ
FT


Avg HC Results
30
25
20
15
10
5
0
g / kg fuel
Low
Mid
High
Throttle Setting
JetA
HRJ
FT


Avg O2 Results
25000
20000
15000
10000
5000
0
g / kg fuel
Low
Mid
High
Throttle Setting
JetA
HRJ
FT


Avg EGT Results
600
500
400
300
200
100
0
g / kg fuel
Low
Mid
High
Throttle Setting
JetA
HRJ
FT

Appendix G: Average Jet A, HRJ, and FT Fuel Flow Results (Salin3 & Salina4)